Quantifying the Financial and Level of Service Implications of Network Variable Uncertainty in Infrastructure Management

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ABSTRACT

There are existing standards and guidelines for the effective management of infrastructure through infrastructure asset management planning (IAM). However, few if any of these standards explicitly address the financial implications associated with the uncertainty that underlies the risk associated with service provision. Without credibly quantifying the potential implications of this network variable uncertainty (i.e. an extreme weather event that affects the performance and costs of many segments within the study network, or the introduction of a new technology that may impact the network cost estimates) infrastructure management systems may actually regularly and significantly over or under estimate the actual financial requirements required to provide services. Therefore, financial projections may actually include a systematic bias. It was hypothesized that a model could be developed that quantifies and communicates the financial implications of network variable uncertainty within the IAM context.

A model was developed to demonstrate how network variable uncertainty could be included in financial planning for infrastructure networks. The model was able to: (1) be applied to various types of infrastructure networks, (2) incorporate network variable uncertainty, (3) compare alternatives and scenarios, and (4) support effective communication of results. The outputs of the model were the average network annual worth (AW) and network present worth (PW). These outputs, along with tornado plots, risks curves, level of service dashboards, and existing budget levels, were used to communicate the impacts of the network variable uncertainty on the financial projections. The model was developed using Excel tools linked to DPL software to utilize probabilistic methods. The Life Cycle Cost (LCC) portion of the model was successfully verified against an existing infrastructure costing tool, the Land and Infrastructure Resiliency Assessment (LIRA) tool developed by the Agri-Environmental Services Branch of Agriculture and Agri-Food Canada. The impact of the network variable uncertainty within the variables was also quantified in terms of levels of service provided by the organization.

The developed model was first applied to a hypothetical twelve segment road network for illustrative purposes. For the hypothetical road network there were four events, representing network variable uncertainty, that were considered. These decisions or events included the: (1)

decision to implement a new technology, (2) event of changing standards, (3) event of increased material costs, and (4) occurrence of an extreme rainfall event. The hypothetical network illustrated that if the defined decisions or events occurred then the expected network AW would increase by 41%. The impacts of decisions or events on the hypothetical network levels of service, stemming from network variable uncertainty, were also considered. The measured levels of service for the hypothetical network included the network financial sustainability indicator (an indicator reflecting the network current budget divided by the network annual worth as a percentage) and the frequency of blading of the roads.

The model was next applied to a case study using the Town of Shellbrook sanitary main network. The Town has a large quantity of aging mains which were constructed in the 1960's and are expected to require renewal in the near term. The network variable uncertainty for the case study resulted from the potential decision to implement a new trenchless technology for the renewal of sanitary mains. The new technology was expected to decrease the renewal costs. However, there was uncertainty as to what percentage of the sanitary mains would be found to be suitable for the new technology. Using the model it was determined that if the decision was made to implement the new technology, there would be an expected reduction of 17% in the network AW. The levels of service that were used for the Shellbrook case study were the network financial sustainability indicator (annual budget / network AW) and the meeting of standards set by regulating bodies. It was determined that the network financial sustainability indicator was sensitive to the decision to implement the trenchless technology, while the meeting of regulating bodies was not. If the decision was made to implement the new technology the network sustainability indicator would be expected to increase from 28% (if the new technology was not implemented) to 34% (if the new technology were implemented).

The model was finally applied to a case study looking at the RM of Wilton gravel road network. The network variable uncertainty for this case study resulted from the potential increase in gravel material costs. The network variable uncertainty represented the magnitude of the annual increase in gravel costs. Given the event of increasing gravel costs the expected network AW would increase by 14%. The levels of service indicators used for the RM of Wilton case study were the network financial sustainability indicator and the frequency of blading. It was determined that the network financial sustainability indicator was sensitive to the event (increasing gravel costs), while the frequency of blading was not directly impacted (although it may be indirectly impacted). If the event of increasing gravel costs were to occur then the network financial sustainability indicator would be expected to decrease from 59% (if gravel costs did not increase) to 52% (if gravel costs did increase).

This research proved that the hypothesis was correct, and that a model could be developed that quantified and communicated the financial implications and level of service impacts of network variable uncertainty for IAM planning. This research illustrated and quantified that IAM planning without accounting for network variable uncertainty, such as: (1) changing technology, (2) changing standards, (3) increasing material costs, and (4) extreme weather events, managers may introduce a systematic bias into long term planning. Network variable uncertainty can significantly impact the projected expenditures required for the long term provision of services. Infrastructure managers and decision makers need to manage infrastructure in a sustainable way over the long term in the face of uncertainty. It is necessary that decision makers have information regarding the impacts of network variable uncertainty on both LCCs and levels of service to make fully informed decision.

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LIST OF ABBREVIATIONS

AASHTO – American Association of State Highway and Transportation Officials

AM – Asset Management

AW – Annual Worth

FCM – Federation of Canadian Municipalities

IAM – Infrastructure Asset Management

IIMM – International Infrastructure Management Manual

LCC – Life Cycle Cost

LCCA – Life Cycle Cost Analysis

IPWEA – Institute of Public Works Engineering Australasia

ISO – International Standards Organization

PW – Present Worth

TAC – Transportation Association of Canada

USDOT – United States Department of Transportation

VDOT – Virginia Department of Transportation

CHAPTER 1 INTRODUCTION

1.1 Background

Infrastructure plays a critical role in the overall health and safety, quality of life, and the competitiveness of municipal economies (ASCE, 2014). As such, the effective management of municipal infrastructure must be a priority for municipal service providers. Infrastructure network managers, without credibly quantifying the potential implications of uncertainty, and including this uncertainty in estimates of financial requirements, may actually regularly and significantly over or under estimate the actual financial requirements required to sustain infrastructure networks. There are existing standards and guidelines to support the cost effective management of infrastructure, specifically in how to deal with predicting infrastructure expenditures, defining levels of service, and managing risks. However, few if any of these standards explicitly address the financial implications associated with the uncertainty that underlies the risks. Without quantifying and including uncertainty within the financial requirements of managing an infrastructure network, these estimates of financial requirements may actually include a systematic bias.

In recent years the effective management of infrastructure has become increasingly important, unfortunately it has also become increasingly complex as communities continue to provide both existing and new services in the face of a changing reality. There are four major challenges facing municipal organizations in the current management of their infrastructure: (1) additional downloaded infrastructure from upper tiers of government, (2) aging infrastructure, (3) increased expectations for levels of service, and (4) increased demand to demonstrate value for money (FCM, 2005). These factors make the effective management of infrastructure increasingly important.

Each of the four factors increasing the complexity of infrastructure management are important to understand. One of the most significant changes in the management of infrastructure is the additional downloaded infrastructure from upper tiers of government. In fact, ‘today, municipal governments are responsible for more than 60 percent of Canada’s infrastructure, up from 34 percent in the 1960’s’ (FCM, 2012). This downloading of infrastructure has increased the amount of infrastructure being managed by municipalities without necessarily increasing the resources available to do so.

Another significant challenge in managing infrastructure is the amount of aging infrastructure. When considering Canadian public infrastructure, ‘most [was] built between the 1950s and 1970s, and much of it is due for replacement’ (Mirza, 2007). Aging infrastructure requires funding for near term renewal as well as increased costs to maintain and operate prior to renewal, which may result in increasing annual costs to provide the same, or an even lower, level of service. When discussing required infrastructure renewals, it is critical to emphasize that any renewal or replacement of infrastructure should be reviewed to ensure that it is a strategic investment and justifiable based on criticality, usage, and other factors. Organizations should not replace infrastructure for the sole reason that it continues to provide a service that currently exists.

The third significant challenge in managing infrastructure is the increased expectations for levels of service. The level of service expectations in municipalities has changed drastically over the past few decades. This is partially due to higher standards and regulations set by upper levels of government (e.g. water and sewer standards) as well as increased community expectation (e.g. dust-free surfaced roads as opposed to gravel roads). Part of this expectation for increased levels of service is a direct result of the lack of communication, to users of services, in quantifying the true cost of services. Without a well-defined link between level of service and the associated cost, it is difficult for users of the service to make informed decisions about affordable expectations for levels of service.

The fourth challenge discussed in managing infrastructure is the demand, by upper tiers of government and the general public, for the public sector to demonstrate value for money and effective management (e.g. value for money audits, changes to infrastructure accounting requirements, and infrastructure report cards). ‘Public skepticism of government, combined with an increasing preference in recent years for using private-sector management approaches in the public sector, has led to demands that government be more accountable and operate more like a private business’ (USDOT, 2013).

It is apparent that the management of municipal infrastructure is not an easy task, and for many municipalities it is only becoming more difficult. To address this global problem, a number of strategies and tools have emerged internationally to support this endeavor. One practice used internationally to assist in the management of public infrastructure is infrastructure asset management (IAM). According to the International Infrastructure Management Manual (IIMM), ***IAM is the 'systematic and coordinated activities and practices of an organization to optimally and sustainably deliver on its objectives through the cost-effective life cycle management of assets'*** (NAMS and IPWEA, 2011). IAM plans can support municipal management of infrastructure by increasing cost-efficiency by minimizing life cycle costs, establishing service levels that better meet customer needs and affordability, increasing the accountability and transparency in decision making, and having services that are funded in an equitable and sustainable way over the long term (NAMS and IPWEA, 2011).

An IAM plan is, in essence, a plan for the management of the infrastructure required to deliver public services. Some of the key aspects of an IAM plan include: details on the assets included in the plan, current and future levels of service, life cycle costs of providing the service, the risks associated with providing the service, future demands on the service, and financial forecasts (NAMS and IPWEA, 2011). While the detailed components of an IAM plan can be complex, the core of IAM is a discussion regarding the balance between the: (1) level of service, (2) cost to provide service, and (3) risks associated with providing the service (NAMS and IPWEA, 2011). As illustrated in Figure 1.1, if any one of these three components is altered the other two would be impacted as these components are inter-dependent. For example, if the level of service is reduced the cost to provide the service may decrease, but the risks associated with providing the service may also increase.

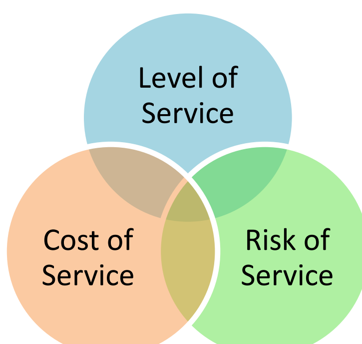

Figure 1.1: Inter-relationship between Level of Service, Cost and Risk

As level of service, cost of service and risk of service are key components in the IAM discussion, it is necessary to ensure that these terms are well defined. The level of service is an indication of the quality, functionality and capacity of the service being provided and at a sophisticated level of IAM, these service levels are set in consultation with stakeholders (NAMS and IPWEA, 2011). The cost of service refers to an estimate of the full life cycle costs (LCCs) associated with the provision of the service. LCCs encompass all of the costs that are anticipated to occur throughout the provision of the service and may include: capital, operating, maintenance, renewal, and disposal costs. The risk of service is defined as the 'threat to [service] operations caused by extreme events, other external hazards, and from asset failure arising from any cause' (AASHTO, 2013). Risk can be considered as the threat of significantly impacting the ability to provide the service at an adequate level. Having a common understanding of the level of service, cost of service, and risks associated with the provision of service are the foundation for a meaningful asset management discussion.

While level of service, cost of service and risks associated with service provision are the pillars of an asset management discussion, arguably, the risks associated with service provision is the least defined in application to IAM (AASHTO, 2013). Understanding and managing risk is an important part of managing infrastructure as there are risks in most, if not all activities, that organizations undertake. The management of risk is more important in some circumstances than others. The management of risk is especially important in the provision of public services, which requires organizations to have a strong understanding of risk as well as the ability to illustrate due diligence in their risk management of service provision (NAMS and IPWEA, 2011).

For the purpose of this research it was also necessary to clarify between the concepts of risk and uncertainty. Uncertainty is generally defined as being indeterminate as to the value of a variable in a way that represents the observed values of that variable (Oxford University Press, 2014). Risk is defined in the IIMM as the 'result of uncertainty' (NAMS and IPWEA, 2011). Risks are the effects, either positive or negative, of uncertainty upon an agency (USDOT, 2012). This research focused not on the risks per se, but rather on explicitly, and credibly, quantifying the uncertainty that is underlying the risks.

There are a number of well documented approaches for the identification, assessment and treatment of risks. One of the approaches most recognized in IAM guidelines is the International

Standard ISO 31000 Risk Management Principles and Guidelines (NAMS and IPWEA, 2011; AASHTO, 2013; BSI Standards Publication, 2014). The main steps of assessing and managing risk as laid out in ISO 31000 are shown in Figure 1.2.

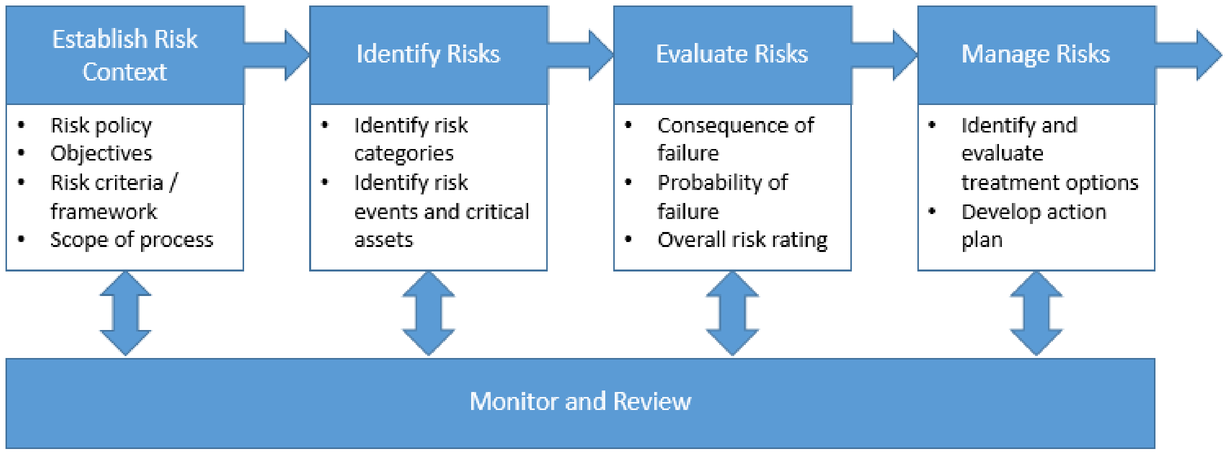

Figure 1.2: Risk Management Modified from ISO 31000 (NAMS and IPWEA, 2011)

While the ISO 31000 offers guidance on establishing context, identifying risks, evaluating risks and managing risks, it does not talk explicitly about quantifying financial uncertainty in a credible way (ISO, 2009). Within the context of IAM planning, if organizations want to plan for the financial requirements of providing services it is critical that they quantify the financial implications of the uncertainty and understand the impacts of uncertainty on the LCCs of providing the service. Without quantifying the financial implications of uncertainty, public agencies may be seriously misrepresenting and inadequately planning for the expected costs of providing public infrastructure. According to the ISO asset management standard ‘The organization’s risk-based decision making processes can become more effective by addressing asset and financial risks together, and by balancing performance, costs and risks’ (ISO, 2014). It is critical that the uncertainty underlying risks be quantified in terms of financial implications for service provision.

As discussed, the focus of this research was on the uncertainty that is underlying the risks within the IAM process. In defining how uncertainty can be included in IAM planning it is important to differentiate between what will be called network variable uncertainty and local variable uncertainty. Network variable uncertainty represents uncertainty with the ability to impact either all, or a significant portion, of the infrastructure network. Network variable uncertainty generally results from the occurrence of a decision or event. Network variable uncertainty is not the same as local variable uncertainty which would not have a significant impact to the network but rather just to an individual asset. When managing infrastructure at the network level, the network level variables are of more concern than the local variable uncertainty. To further explain the difference between network and local variable uncertainty consider a model that has been developed to estimate the required network expenditures. The estimate of the required network expenditures is the summation of the expenditures for each asset. Each asset has individual attributes which drive the costs associated with the individual asset, but can be combined to estimate the network LCCs. This conceptual model shown with no uncertainty is illustrated in Figure 1.3. The round circles identified with asset numbers represent the required annual expenditure by network asset.

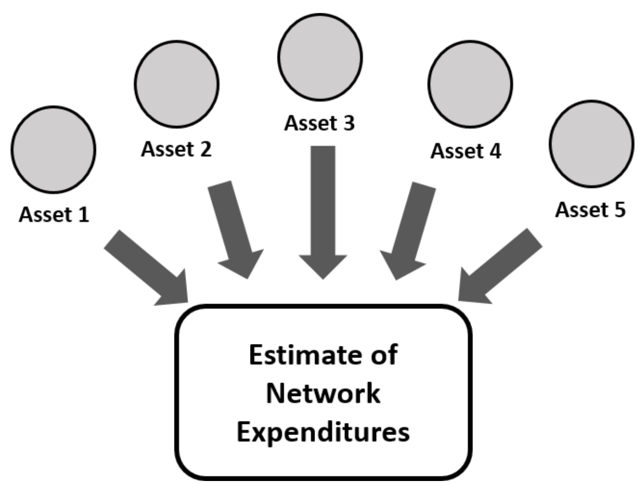

Figure 1.3: Model Estimate Network Expenditures with Variables

Local variable uncertainty is uncertainty that would occur in the individual assets that make up the model. There may be uncertainty in one or more of the assets. An example of a model with local variable uncertainty is shown in Figure 1.4. In this conceptual example Assets 1, 3, and 4 all have local variable uncertainty (represented by the random shape surrounding the annual asset expenditure, or numbered circle) which may impact the result of the model by impacting the LCCs of the individual assets. However, since the model output is the summation of the individual asset expenditures it is expected that the local uncertainty within each of the assets would somewhat balance each other out at the network, model output, level (i.e. one road within the segment may last a shorter period than expected while another road lasts longer, and at the network level the average of these lives may provide a reasonable estimate). Some uncertainty might increase individual asset costs while others might decrease the costs (cost increases and decreases are indicated by the arrows within the numbered assets expenditure projections). This local variable uncertainty is illustrated in Figure 1.4.

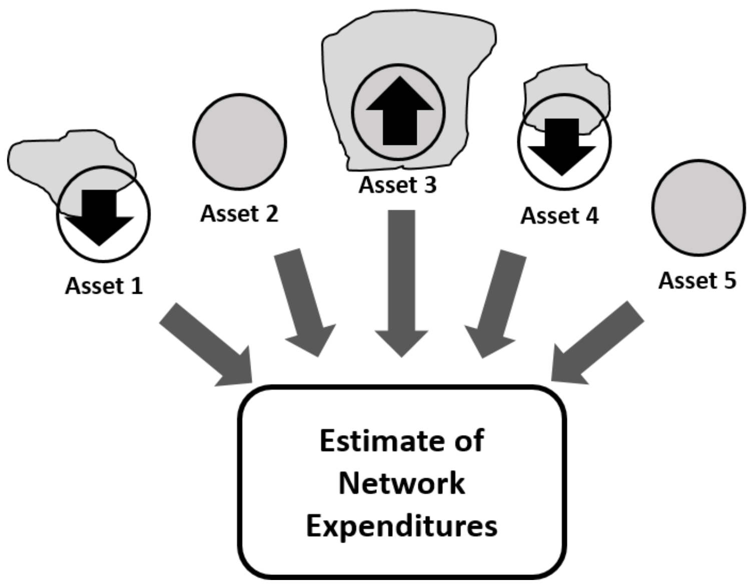

Figure 1.4: Model Estimate Network Expenditures with Local Uncertainty

This individual asset uncertainty, or local uncertainty, would not have as significant an impact on the network LCCs as network variable uncertainty that impacted the entire network. Network variable uncertainty on the other hand would have the potential to significantly impact the output of the model (i.e Network LCCs). This network variable uncertainty would likely result from the occurrence of a decision or event and may impact all or a significant portion of the network model (shown with the uncertainty connected to multiple numbered assets in Figure 1.5). It would be expected that the LCCs of the portion of the network impacted would either mainly decrease or increase as a result of the external event. As network variable uncertainty is expected to significantly impact a significant portion of the network, it would also be expected to significantly impact the model output (network LCCs). This is illustrated in Figure 1.5, where the costs of the individual assets have, with the exception of Asset 4, all increased as a result of the occurrence of the external event.

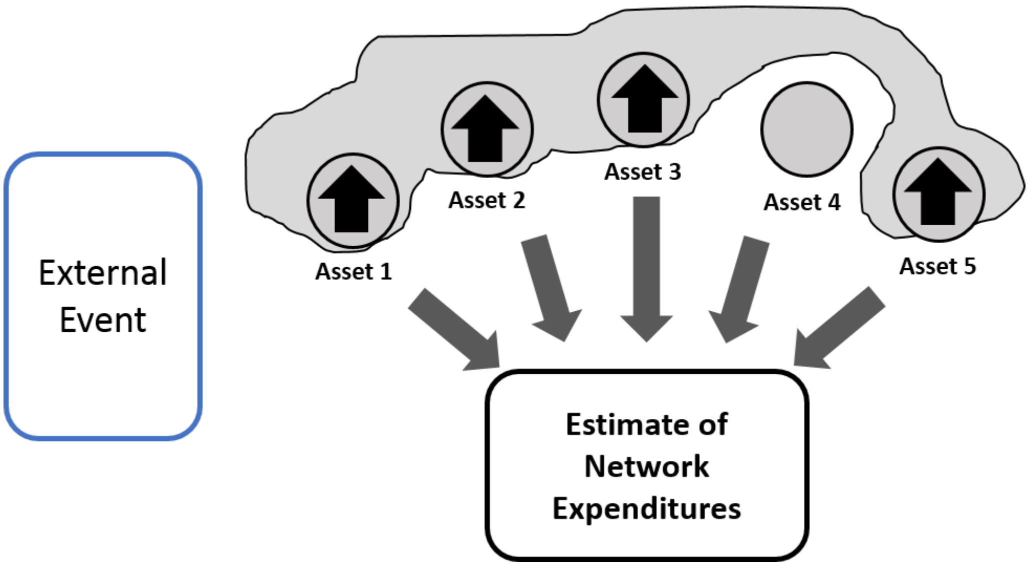

Figure 1.5: Model Estimate Network Expenditures with Network Variable Uncertainty

An illustrative example of the relationship between local and network variable uncertainty is a bus full of passengers. The life expectancy of each individual passenger could be considered to be determined by their local variables (e.g. age, health, history, diet, etc.). However, the life expectancy of the passengers may also be impacted by network variables (e.g. weather events, mechanical failure, driver error, etc.). The life expectancy of any individual passenger, based on local variables, would not be expected to impact the other passengers. However, if an external event occurred, the life expectancy of all, or a significant portion of, the passengers could be impacted. The relationship between local and network variable uncertainty described in the bus example can readily be applied to a rural road network. Examples of local variable uncertainty might be the useful life of the asset segment based on maintenance history, or the expected renewal cost based on the soil condition. For comparison, examples of network variable uncertainty might include uncertainty in asset replacement resulting from an extreme weather event, or the increased cost of treatments due to an increase in material costs due to scarcity. While there are a vast number of network variable uncertainties that could be considered, based on consultation with infrastructure managers and past experience, this research focused on four: (1) increasing standards, (2) changing technology, (3) increasing material costs due to scarcity, and (4) extreme weather events.

Network variable uncertainty was the focus of this research due to its significant impact on service provision at the network level. Since network level variables can impact a significant portion of the network it is assumed that they have the potential to significantly impact the LCCs associated with service provision. One of the key purposes of IAM is to assist decision makers by providing a ‘fact-based dialogue between system users and other stakeholders […]. This results from relevant, objective, and credible information being accessible to all participants in the decision-making process […]. The information underlying Asset Management […] results in an improved understanding of the economic trade-offs, return on investment, and potential value of the end product’ (USDOT, 1999). However, to make a truly informed decision it is ***critical that the network variable uncertainty be included and communicated through the LCC estimates used to estimate required funding***. By including network variable uncertainty, various alternatives and scenarios can be weighed against each other in a meaningful way.

The purpose of IAM planning is to effectively manage infrastructure in a way that sustainably provides public services to users. There is a strong consensus in existing IAM standards and guidelines that IAM is a balancing act between levels of service, cost of providing service, and risk of providing service. However, there is little guidance from existing standards on how to include the financial implications of network variable uncertainty within the IAM plan to ensure that the infrastructure is being managed in a sustainable way. ‘While the importance of risk management is clear, few resources exist to help [service providing] agencies integrate risk management into asset management’ (AASHTO, 2013). Therefore there is a need for the development of a model that illustrates how to credibly quantify, and effectively communicate, the financial implications and level of service impacts of network variable uncertainty within IAM planning.

1.2 Hypothesis

The hypothesis of this research was that a model could be developed that credibly quantifies, and effectively communicates, the financial implications and level of service impacts of network variable uncertainty within the IAM context. The network variable uncertainty would be included by modeling these variables probabilistically.

1.3 Objectives

The overall goal for this research was to illustrate and quantify that IAM planning without accounting for network variable uncertainty, such as: (1) changing technology, (2) changing standards, (3) increasing material costs due to scarcity, and (4), extreme weather, events could lead to systematic under or over estimates of infrastructure requirements and lead to decisions not necessarily in the best interests of the municipality.

Specific objectives required in achieving this goal include:

1. The development of a model that estimates LCCs and future expenditures for asset management purposes while incorporating network variable uncertainty, using probabilistic methods.
2. Illustration of the significance of the impact of network variable uncertainties within IAM planning using Saskatchewan case studies.
3. Discussion on how the inclusion of network variable uncertainty in IAM planning may impact how planning decisions are made.

1.4 Scope

The scope of this research included the development of an LCC model that illustrated how network variable uncertainty can be included within IAM. The model that was developed is applicable to any type of infrastructure network. The model was further tested using two Saskatchewan municipal case studies. These case studies show both the application of the model to real world scenarios and the impact of not including uncertainty in future expenditure estimates.

This research did not deal explicitly with the complexities of increasing frequency and severity of extreme weather events. The examples used for demonstrating extreme weather event uncertainty was included at a high level, and for illustrative purposes only, within the analysis. It is expected that to include uncertainty in LCC resulting from extreme weather events would require collaboration with hydrological engineers / modelers and other parties able to estimate damages resulting from those events.

The costs used for the estimated life cycle costs throughout this research were provided by the communities involved in the case studies. These costs are based on the best available information within the communities. These costs are not assumed to be average estimates.

This research did not consider local variable uncertainty which would still be expected to occur at the individual asset level.

1.5 Methodology

Element 1: Literature Review

- Task 1: Review of key IAM concepts including life cycle costs of infrastructure, levels of service, and risks associated with service provision.
- Task 2: Review of the inclusion of uncertainty in existing international asset management standards and guidelines.
- Task 3: Review of the inclusion of uncertainty in North American IAM standards and guidelines.
- Task 4: Review of the inclusion of uncertainty in current infrastructure related literature.
- Task 5: Summary of the current status of quantification of uncertainty in IAM standards, guidelines, and literature.

Element 2: Development of the Deterministic Model

- Task 1: Development of a deterministic LCC model that can be utilized for any type of infrastructure network. The LCCs included initial construction costs, operating and maintenance costs, renewal costs, and disposal costs. The outputs of the model are the average network AW and the estimated PW.
- Task 2: Development of a method to illustrate level of service measures. It is essential that the levels of service are part of the IAM discussion.

Element 3: Inclusion of Network Variable Uncertainty in the Model

- Task 1: Development of a process to consistently define network variable uncertainty scenarios.
- Task 2: Development of a process to support the definition and transparent communication of the impact of the network variable uncertainty to the LCCs and levels of service.
- Task 3: Revision of the model to include network variable uncertainty into the LCCs. This was done through augmentation of the deterministic LCC model using probabilistic methods.
- Task 4: Linkage of the LCC model to Decision Analysis Software (DPL)[1]. This required the development of a linked influence diagram based on the network variable uncertainty. Review of the outputs of DPL including tornado plots, risk curves, and expected values.
- Task 5: Revision of the level of service measures to include network variable uncertainty.

Element 4: Application of the Model to a Hypothetical Network

- Task 1: Definition of the hypothetical network, along with the uncertainty events that were considered.
- Task 2: Calculation of the network base case LCCs using the model. The model was calibrated using ‘typical’ treatment timing and costs for a rural road network established in the Rural Road Costing Model (Saskatchewan Municipal Asset Management, 2014) as well as other data available from Saskatchewan rural municipalities (RM’s).
- Task 3: Verification of the developed model using the Government of Canada Landscape Infrastructure Resiliency Assessment (LIRA) tool (VEMAX, 2010).
- Task 4: Definition of the network variable uncertainty scenarios and impacts. For the hypothetical network the network variable uncertainties included: (1) increasing standards, (2) changing technology, (3) increasing material costs due to scarcity, and (4) rainfall event.
- Task 5: Calculation of the lower and upper bound outcomes for each of the uncertainty scenarios.
- Task 6: Calculation, using DPL, of the tornado plots, risk curves and expected values for the inclusion of the uncertainty scenario.

[1] DPL is a software program that supports decision and risk analysis. DPL 7 Standard was used for this research.

- Task 7: Comparison of the results of the AW for the base case and the network variable uncertainty scenarios.
- Task 8: Definition of the level of service indicators for both the base case and for the network variable uncertainty scenarios.

Element 5: Case Study 1 – Town of Shellbrook

- Task 1: Definition of the case study network which consisted of the Town of Shellbrook sanitary main network.
- Task 2: Review of base case LCCs given the consideration that the case study was an existing network and the network may be in a period of high or low renewals.
- Task 3: Calculation of the typical LCCs for the base case. The inputs for the LCCs came from Town staff.
- Task 4: Definition of the network variable uncertainty scenario and the impacts of the network variable uncertainty. For this case study the network variable uncertainty scenario included the decision to implement a new technology for the renewal of the sanitary mains.
- Task 5: Quantification of the potential event outcomes, given the uncertainty, using DPL. This was done through the use of tornado plots, risk curves, and expected value calculations.
- Task 6: Comparison of the network average AW for the base case and the network variable uncertainty scenario.
- Task 7: Definition and comparison of the level of service indicators for both the base case and the uncertainty scenarios. The indicators used for this case study included network financial sustainability indicator and the meeting of sanitary sewer standards and regulations.

Element 6: Case Study 2 – Rural Municipality of Wilton

- Task 1: Definition of the case study network which consisted of the Rural Municipality (RM) of Wilton's gravel road network.
- Task 2: Review of the upcoming LCCs given the consideration that the case study was an existing network and the network may be in a period of high or low renewals.
- Task 3: Calculation of the typical LCCs for the base case. The inputs for the LCCs came from RM staff.
- Task 4: Definition of the network variable uncertainty scenario and the impacts of the uncertainty on the network AW. For this case study the uncertainty scenario included the increase in gravel material costs due to scarcity which impacted the cost of operating and maintenance and renewal activities.
- Task 5: Quantification of potential event outcomes, given the network variable uncertainty, using DPL. This was done through the use of tornado plots, risk curves, and expected value calculations.
- Task 6: Comparison of the network average AW for the base case and the network variable uncertainty scenario.
- Task 7: Definition and comparison of the level of service indicators for both the base case and the uncertainty scenario. The indicators used for this case study included the network financial sustainability indicator and the frequency of blading of the roads.

1.6 Layout of Thesis

Chapter one of this report provides background to the reader on the topic of infrastructure management, and reference for why the inclusion of network variable uncertainty within the management of infrastructure is important. There is a discussion on the distinction between local and network variable uncertainty. This chapter includes the hypothesis, research objectives and research methodology.

Chapter two consists of a literature review on the topic of infrastructure asset management and the inclusion of uncertainty in infrastructure planning. This chapter includes an evaluation of the current standards, frameworks, and guidelines that are available locally and internationally to support infrastructure management. The chapter also ends with a summary of terms and concepts used throughout the paper. This is followed in Chapter 3 by a short mathematical example. The purpose of the example is to clarify terms and concepts that were used throughout this research and discussed through the following chapters of this report.

Chapter four provides an outline of the development of the basic LCC deterministic model. This section looks at the basic formulas for calculating the LCCs, such as operating, maintenance, and renewal costs that were used as inputs to the model. There are also definitions of the calculations used for the model outputs which are the network AW and PW.

Chapter five was an augmentation to the deterministic model, developed in Chapter three, to include network variable uncertainty using probabilistic methods. This section outlines the formulas that were used to include the uncertainty in the model. This chapter also includes a verification of the model.

Chapter six was the application of the model to a hypothetical rural road network. There were four uncertainty scenarios including: (1) changing standards, (2) new technology, (3) increasing gravel material costs due to scarcity, and (4) the occurrence of a rainfall event. These uncertainty scenarios were compared against the base case AW. The impact of the uncertainty was quantified in terms of financial implications as well as level of service impacts.

Chapter seven illustrates the first case study. This case study is the Town of Shellbrook sanitary main network. The uncertainty scenario that is considered is decision to implement a new trenchless technology for renewal of the sanitary mains. This chapter reviews the impact of the uncertainty scenario to both the network AW and the levels of service.

Chapter eight consists of the second case study. This case study is the RM of Wilton gravel road network. The uncertainty scenario that is included is the event of increasing gravel costs due to an increasing scarcity of resources. This chapter considers the impacts of the network variable uncertainty on the network AW and levels of service.

Chapter nine summarizes the findings and conclusion of this research. Recommendations for future work are also included in this section.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The three pillars of asset management (AM) commonly discussed in the literature are the cost to provide service, the level of service, and the risk associated with providing the service. This balance of risk, cost, and level of service is dependent on management of infrastructure and is a key component of organizations providing value for money (ISO, 2014). The focus of this research is on the quantification and communication of the network variable uncertainty underlying the risks associated with infrastructure supported services. This research was selected as it was postulated that there was a lack of guidance in existing standards regarding credibly quantifying and effectively communicating uncertainty in a way that supports the decision making process. Without defining the implications of uncertainty, from both a financial and a level of service perspective, it is impossible for decision makers to make fully informed decisions.

A number of IAM standards exist to guide organizations in managing infrastructure. There are international standards such as the *ISO 55000 Asset Management Manual* (ISO, 2014) and the *International Infrastructure Management Manual* (IIMM) (NAMS and IPWEA, 2011). There are also more localized or asset specific standards such as those released by the Transportation Association of Canada (TAC) (TAC, 2013) or the Department of Transportation (USDOT) (USDOT, 1999) and the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO, 2013) in the United States. While these local and specific standards may have different audiences or be catered specifically to one type of service delivery, they still have many commonalities with the more generic IAM guidelines.

2.2 Important Infrastructure Asset Management Concepts

The international and local standards referenced above all recognize the need for, and importance of, managing infrastructure. This is partially due to increased awareness by stakeholders that many municipalities have not been making strategic decisions regarding management and investment into infrastructure, which is impacting the long term sustainability (NAMS and IPWEA, 2011). The majority of these standards also recognize the three critical pillars of asset management being the: (1) cost to provide the service, (2) levels of service, and (3) risks associated with service provision. These concepts are discussed in more detail in the following sections.

2.2.1 Life Cycle Costs

LCCs are all of the costs that are associated with owning and operating an asset over its period of use. The practice of making decisions based on full LCCs is important in the management of infrastructure. Historically, many organizations have focused on minimizing initial capital costs and ignored the full cost of owning and operating the asset over its life. This can result in a significant underestimate of the full costs of the service since the capital costs can be as little as 10-20% of the full LCCs (NAMS and IPWEA, 2011). Examples of activities that may be considered in the full LCCs of providing services may include: planning, new construction, acquisition, operations, maintenance, preservation activities, replacement, upgrades, and disposal (NAMS and IPWEA, 2011; AASHTO, 2013). The practice of using LCCs for analysis is not a new concept in the management of infrastructure and there are various guidelines and tools to support users in considering full LCCs such as the *Life-Cycle Cost Analysis Primer* released by the USDOT (USDOT, 2002).

2.2.2 Levels of Service

The level of service is an indication of the quality, function, and capacity of the service being provided. Levels of service are a key component of IAM. Levels of service are used to support understanding of customer service priorities, and willing to pay. Levels of service are also used to measure service performance (NAMS and IPWEA, 2011). According to a best practice guide to establishing levels of service released by the Federation of Canadian Municipalities (FCM) and the National Research Council (NRC), levels of service are critical in the management of infrastructure as they support good decision making, facilitate sustainable development, help provide an understanding of environmental impacts, and aid with community interaction and consultation regarding infrastructure (Infrastructure Canada, 2003).

Levels of service (LOS) are often broken into two categories, customer and technical. Customer LOS represents the customer's point of view on how they have received the service. Customer LOS are expressed in easy to understand measures (e.g. appearance, frequency of disruption). Technical levels of service are used to achieve strategic objectives and are generally expressed in technical terms (e.g. ride, roughness, breaks per meter) (AASHTO, 2013). Levels of service are generally set to represent the priorities of the organization and community. Since LOS is closely linked to available funding in many cases the biggest driver of LOS is the willingness to pay of the user. This is less often the case where there are regulations regarding the quality of a service (e.g., specific minimum water and wastewater treatment standards) (Infrastructure Canada, 2003). The success of an organization to meet set levels of service is usually reviewed through performance monitoring, which is a review of the actual performance of the asset or service being provided (Infrastructure Canada, 2003).

2.2.3 Risk

Risk is defined in the *IIMM* as the 'result of uncertainty' (NAMS and IPWEA, 2011). The effect of uncertainty on risk may be positive, negative, or different from what was expected (AIRMIC, et.al, 2010). 'Risk management is an important part of asset management […] However, there are few practical tools yet available in the marketplace, with many practitioners managing this aspect with the aid of spreadsheets or custom built databases' (AASHTO, 2013). The fact that there are few tools available to credibly quantify risk (or the underlying uncertainty) is one of the key purposes of this research. According to the AASHTO *Transportation Asset Management Guide* the various types of risks can be grouped into four key areas: (1) natural events and hazards, (2) external impacts on the agency, (3) physical asset failures, and (4) operational risk events (AASHTO, 2013).

The frameworks and guidelines that exist to manage risk often refer to the approach outlined in the ISO risk management standard *ISO 31000* (ISO, 2009). The *ISO 31000* standard specifies that it is not intended for certification purposes, but it does provide a risk management guide that can be applied globally (Lajtha, 2012). The framework outlined in the *ISO 31000* document and referenced by others is included in Figure 2.1.

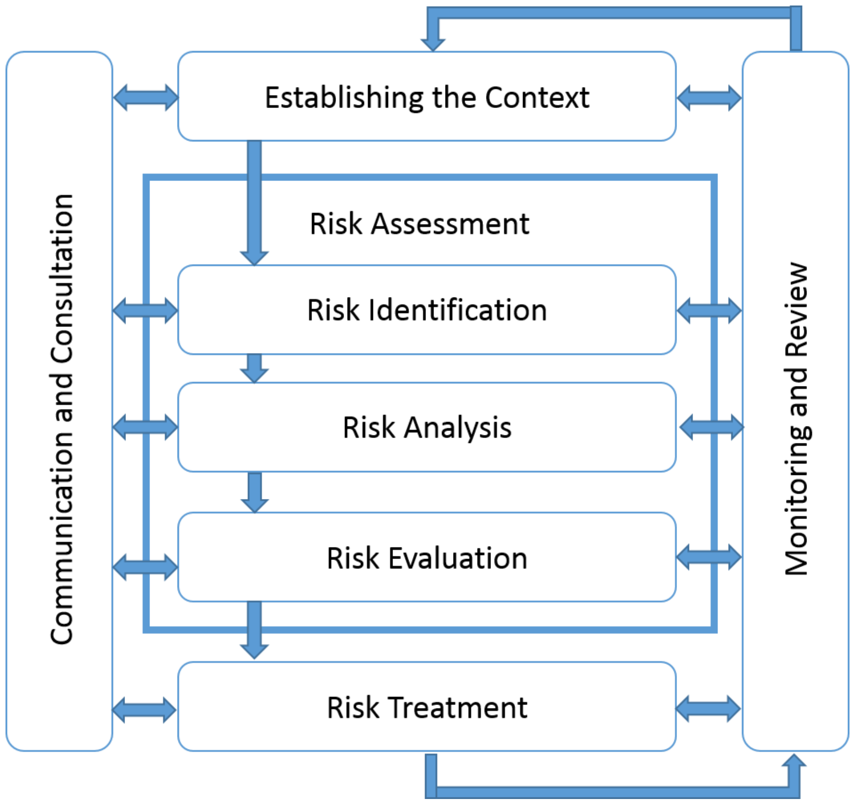

Figure 2.1: Derived from ISO's Risk Management Framework (ISO, 2009)

The general steps outlined in the ISO risk management framework are explained in the *IIMM*. Firstly, by establishing the context and understanding the internal and external environment that the organization is operating in, along with aspects such as the organizations risk tolerance. Secondly, by identifying the risks by establishing a catalogue or register of risks to be considered and analyzed. Thirdly, analyzing the risks by defining the likelihood of them occurring and the consequence if they do occur. The method of analysis is to be determined by the user. Fourthly, an evaluation as to whether the risks are acceptable to the organization or if further risk management or mitigation measures need to be taken. Where necessary a risk treatment plan is developed to reduce the level of risk. The whole process is done within the context of ongoing monitoring and review of the risks and risk management process and communication and consultation (NAMS and IPWEA, 2011).

2.2.4 Summary of the Pillars of AM

While each of the three pillars of asset management: (1) levels of service, (2) cost of service provision, and (3) risk of service provision are integral components, the focus of this research was on the uncertainty underlying the risks. While risk is discussed in most of the available IAM guidelines, there is a lack of discussion on how to include uncertainty in LCC estimates or the estimates of required funding. The AASHTO IAM guidelines go so far as to say that ‘while the importance of risk management is clear, few resources exist to help [service providing] agencies integrate risk management into asset management’ (AASHTO, 2013).

2.3 Inclusion of Uncertainty in International Standards and Guidelines

The most recognized international standards in regards to infrastructure asset management are the *IIMM* and the *ISO 55000* Asset Management standard. These were reviewed to better understand how the issue of uncertainty was addressed. While both of these standards directly reference risk, this review is focused on the uncertainty underlying the risk. In the context of IAM, and this research, risk was defined as ‘the effect of uncertainty on objectives[2]. The main focus was how the impacts of this uncertainty was included in the literature in terms of impacts to both LCCs and levels of service.

2.3.1 International Infrastructure Management Manual

The *IIMM* was developed jointly between Australia and New Zealand. The *IIMM* is one of the most referenced asset management guides. The concept of risk management is highlighted and reiterated throughout the guide. Within the section on demand forecasting there is reference to the inherent uncertainty within forecasting, as well as an indication that the consequences associated with the uncertainty can in fact be quite large. The guide discusses that a crucial part of advanced IAM is understanding the risks associated with demand forecasting. For the purposes of risk management the *IIMM* guide is consistent with the *ISO 31000*. The *IIMM* outlines the need for the risk management process to both impact and influence the decision making process. An emphasis is made in the *IIMM* that any efforts put into either the definition or the management of

[2] This research focuses on uncertainty and not risk. Uncertainty drives the risks.

risks need to be weighed against the potential risk impacts (NAMS and IPWEA, 2011). The risk management process is discussed as a fairly qualitative discussion. The guide talks about the need to perform a sensitivity analysis for important assumptions and estimates. The Guide does not refer to quantifying the financial impacts of uncertainty.

2.3.2 ISO:55000 Asset Management Standard

The *ISO:55000* is one of many standards released by the ISO and was developed through consultation with international representatives. This standard has many references to the importance of risk management within the IAM process. There is also a direct reference to the fact that the decision making process will become much more effective if the asset and financial risks are addressed in an integrated way. The risk management ISO standard, *ISO 31000*, is referenced as the recommended process, and as an additional resource, for risk management (ISO, 2009). Within the ISO AM standard there are few references specifically to uncertainty. The ISO AM standard has a useful definition of uncertainty as the 'state, even partial, of deficiency of information related to, understanding, or knowledge of, an event, its consequence, or likelihood' (ISO, 2014).

The ISO AM standard references the importance of risk management within the IAM planning process, and ultimately links uncertainty and risk. The standard illustrates that there may be significant impacts resulting from uncertainty. However, there is no discussion on quantifying uncertainty by including it in financial projections or in level of service discussions.

2.4 Inclusion of Uncertainty in North American Standards and Guidelines

While the *IIMM* and the *ISO 55000* are the established international AM guides, there are numerous guides and standards that have been released in recent years. These North American standards and guidelines were reviewed for direction on the quantification and communication of uncertainty underlying risks associated with service provision.

2.4.1 Canadian Standards and Guidelines

In 2013 the Transportation Association of Canada (TAC) released the most recent version of the *Pavement Asset Design and Management Guide* (TAC, 2013). The TAC Guide suggests that asset management should be able to demonstrate the impact of variations in budget levels and changes to standards on both the levels of service and the risks (TAC, 2013). The Guide also references the fact that one of the primary objectives of the asset management system is to have the ability to predict changes in future expenditures (TAC, 2013). The Guide does not talk about including uncertainty in those future estimates. There is no recommendation, in the TAC guide, for organizations to quantify uncertainty within asset management planning.

In the last number of years there have been two reports released by major infrastructure players in Canada. These include *The Canadian Infrastructure Report Card Asset Management Primer* (FCM, et.al, 2014) and the *Model Framework for Assessment of State, Performance, and Management of Canada's Core Public Infrastructure* (NRC et. al., 2009). They were both developed with a number of partners. The *Canadian Infrastructure Report Card* does not specifically refer to uncertainty or the need to include uncertainty and risk in financial estimates. There are references to risk within the report but it is mainly in terms of the impact of asset failure. The *Model Framework for Assessment of State, Performance, and Management of Canada's Core Public Infrastructure* refers to the risks to Canadian public infrastructure as well as the impact of climate change and other environmental issues that may be of concern. This framework discusses the need to investigate the effective integration of risk management into the decision making process, but does not provide suggestions on how this can be done (NRC et. al., 2009).

The Ontario Ministry of Economic Development, Employment & Infrastructure has recently implemented funding changes by requiring asset management plans for access to provincial funding. To support Ontario municipalities in developing AMPs, the Ministry has released an asset management toolkit which includes a guide (Ontario Ministry of Infrastructure, 2012). The Ontario Guide discusses the need to define and manage risks. The Guide also refers to the importance of considering other factors which might impact the management of the infrastructure networks, including climate change and the potential implementation of new technology. There is a discussion regarding the use of quantitative and qualitative measures being used in assessing risks. 'Risks … can be scored based on quantitative measures when reasonable estimates can be made of the probability of the risk event happening and the cost associated with the risk event. Qualitative measures can be used when reasonable estimates of the probability and the cost associated with the risk event cannot be made' (Ontario Ministry of Infrastructure, 2012). The guide does not explain how the costs associated with risk events are included in long term expenditure planning.

The *InfraGuide* is a document that was funded by a number of infrastructure stakeholders in Canada (FCM, 2003). Within the *Innovations and Best Practices Guide* (FCM, 2013), there is no reference to uncertainty. However, there is reference to the need to include the risk of current asset condition within the IAM process. Risk management is referred to as a necessary part of asset management and the process of risk assessment is based on that explained in the ISO 31000 standard. It appears that the risks that are referred to in the *InfraGuide* are primarily those related to asset condition and the organization not meeting established levels of service.

Of the Canadian Guides that were reviewed, there was consistent reference to risk management being a critical component of the infrastructure planning process. There was less direct reference to the impacts of uncertainty, including when and how this uncertainty should be included. There was no direct recommendations or examples of how uncertainty could be quantified and communicated to illustrate the impacts on LCCs and levels of service in a way that supports informed decision making.

2.4.2 United States of America Standards and Guidelines

The United States Department of Transportation (USDOT) has released a number of standards and guidelines to support the management of road networks. A few of the most relevant documents are the: (1) *Asset Management Primer* (USDOT, 1999) , (2) *The Asset Management Overview* (USDOT, 2007), and (3) *The Risk-Based Transportation Asset Management Guide* (USDOT, 2012). These guides talk about the importance of risk management and refer to the use of the *ISO 33000* as a framework for practicing risk management. The USDOT documents discuss the fact that there is inherent uncertainty in the assumptions that impact LCCs such as costs, weather, etc. The USDOT documents also comment on the fact that this uncertainty is the result of risk and recommends that this uncertainty be included in the engineering economic analysis (USDOT, 2012).

In the *Risk-Based Transportation Asset Management Guide*, the USDOT refers to climate change as one of the largest risks, or effects of uncertainty, facing infrastructure managers. Other potentially significant uncertainties exist in increasing costs of providing services, along with funds made available from upper tiers of government. The USDOT indicates that climate change forecasts point towards increased uncertainty and variability in the future (USDOT, 2012). The Guide outlines that in other areas of practice, risk management is accepted as a requirement of the governance role. However, this is not necessarily the case with IAM. That being said, the current status of risk management does not negate the fact that it needs to be explicitly addressed; it is critical that it be included in the decision making process, and that it is effectively communicated to all stakeholders (USDOT, 2012). *The Asset Management Overview* released by the USDOT does not extensively refer to uncertainty, however, it does discuss the importance of communicating the risks and potential uncertainties to decision makers (USDOT, 2007).

These USDOT documents, when compared to other guidelines and frameworks, have more discussion on the impacts or risk as well as the need to include it in the IAM process. These documents also highlight the fact that this sort of information supports informed decision making and needs to be effectively communicated (USDOT, 2012). While these documents demonstrate the importance of including uncertainty and risk in the decision process, none of the USDOT guides reviewed provided specific guidance in how this inclusion of uncertainty could be done within the objectives of IAM.

The American Association of State Highway and Transportation Officials (AASHTO) has released a *Transportation Asset Management Guide* (AASHTO, 2013). The AASHTO Guide indicates that organizations should not ignore uncertainty and risk. There is also discussion that it is critical that risk management is integrated into the decision making level. This guide refers to the fact that the inclusion of risk in asset management planning is relatively new. The method suggested for risk management is similar to that outlined in *ISO 31000:* (1) identification, (2) analysis, and (3) evaluation. As with all other standards reviewed there is no explicit directive in how to quantify the impacts of uncertainty or in how to communicate these impacts to decision makers.

This section has outlined a number of North American Guides that discuss the importance of including uncertainty and risk in the asset management process. While there is a strong consensus on the importance of including uncertainty and risk in asset IAM, there is a large gap in the Guides for how to quantify the potential implications associated with the risks. Many of the Guide's reference the fact that it is necessary that risks are effectively communicated and that this uncertainty may impact the choices made by decision makers. It would seem that without explicitly quantifying the financial implications of the risks, it is more difficult to make decisions in a way that adequately includes the associated uncertainty.

2.5 Inclusion of Uncertainty in Asset Management in Literature

In the literature that was reviewed there were various types of uncertainty that were discussed. These could generally be separated into aleatory and epistemic uncertainties (Pate-Cornell, 2002). Aleatory uncertainty is related to randomness while epistemic uncertainty is related to a lack of knowledge or data regarding a model, system or other. In a review of the impact of uncertainty in models it was determined that uncertainty was impacted most by errors made in forecasting rather than errors in the data or the models (Piyatrapoomi, 2004). While uncertainty can generally be reduced in asset knowledge or systems, there is inherent risk in forecasting the future that may not be able to be significantly reduced.

There are two methods for looking at the LCCs of infrastructure networks. The first is using a deterministic process and the second is using a probabilistic process. The deterministic method uses a 'best' estimate for model variable values and returns a single value result. A probabilistic method takes into account uncertainty within a variable and assigns probabilities to the various model variable values. Results for probabilistic models generally take the form of risk curves illustrating expected, along with lower and upper bound outcomes. Historically, if organizations included the impacts of uncertainty within asset management planning it was done by running various scenarios. By using scenarios to include uncertainty, there is some understanding of the impacts on the final result, however, the full impact of the uncertainty may not be understood. The use of scenarios for inclusion of uncertainty does not allow for forecasting or calculation of the probability of the occurrence (Piyatrapoomi, 2004).

When models take a probabilistic approach they often require extensive computational power as they are frequently based on a Markov process (ManWo Ng, 2011). A main assumption for Markov models is that the current condition and the transition between condition states is known. Having the expertise and systems available for many of these probabilistic tools is likely out of reach for small to medium sized communities. It should also be noted that when uncertainty is not significant to the management of network, the results from a probabilistic model may not vary significantly from a deterministic estimate (ManWo Ng, 2011). However, it may be the case that the significance of various uncertainties may only be determined through the use of probabilistic modelling.

While there are challenges in organizations having the capacity to use probabilistic methods in infrastructure planning, it is generally acknowledged that probability-based approaches are the more rational way to treat uncertainty (Leon, 2005). While a fully probabilistic approach to LCC may not be attainable for all organizations, it should be recognized that probability-based approaches that are simplified to focus on forecasting uncertainty are a reasonable tool for evaluation purposes (Piyatrapoomi, 2004). One of the difficulties with using probabilistic modelling is gathering the necessary data, such as variable value probability. However, this can be solved by utilizing Bayesian methods to define uncertainty in risk (Pate-Cornell, 2002). While the outputs of probabilistic-based approaches (e.g. risk curves) can be difficult to develop, they can also be difficult to interpret and may require expertise to understand properly (Pate-Cornell, 2002). Across all of the literature reviewed there was consensus that while there can be difficulties with probabilistic modelling, the estimates with the inclusion of uncertainty led to better decision making, and more informed decision makers. However, there needs to be consideration of the potential impact of uncertainty and any review of uncertainty needs to be within the context of the potential magnitude of risks and benefits.

In asset management, decisions are regularly made based on financial implications. (M.D. Catrinu, 2011). The potential financial impact of uncertainty can be large, and generally speaking as the numbers of uncertainties increase so does the potential impact (ManWo Ng, 2011) ‘It is the quantification—even a coarse one—of the risks that allows comparing them with mitigation costs and ranking the different options according to their cost effectiveness provided that the method of risk assessment allows for this comparison’ (Pate-Cornell, 2002). When reviewing uncertainty in models it is also necessary to not be overly conservative and have results based on cumulative uncertainties, representing a worst case scenario risk curve (Pate-Cornell, 2002). It is understood that some types of uncertainty will significantly impact the financial estimates required for managing infrastructure, however, there are also uncertainties that will have very little impact. Only by quantifying these potential impacts can the risks be understood and the effective management of these risks occur.

2.6 Summary

There are a number of well-established international asset management guides, frameworks, and standards, as well as numerous guides released in North America. There has been a lot of work done in documenting how to calculate the cost of providing service (USDOT, 2002), as well as how to document the levels of service (NAMS and IPWEA, 2011; Infrastructure Canada, 2003). While there is a significant amount of knowledge and literature surrounding the area of risk management, within the asset management context there is little to no direction for how to explicitly quantify the financial impacts of the uncertainty underlying the risk. The most consistent framework for risk management was the *ISO 31000* which many of the guides and the literature directly referenced as a potential or preferred method.

The current status of quantification of financial and level of service risk in asset management is well described by Piyatrapoomi, when he summarized from a review of literature that ‘only an overview of the importance of risk assessment has been given, but no suggestion has been made on how to incorporate risk into the investment decision making process. However, many types of risk including economic, political, social and other related risk issues have been recognized as crucial criteria for investment decision-making’ (Piyatrapoomi, 2004). So while the importance of risk management has been well established, the tools that are currently available and accessible for small and medium organizations, do not support the quantification of the impact of uncertainty for expenditure projections and levels of service.

CHAPTER 3 CLARIFICATION OF TERMS AND CONCEPTS

Upon review of the existing literature it was found that there was at times confusion in how common terms, (e.g. event, uncertainty, risk, etc.) were used. It seemed prudent to use a basic example to illustrate how specific decision support terms and concepts were used within this thesis. A simple example was used to demonstrate the general process used throughout the model and the analysis completed within this research.

This example looked at the problem of a network manager planning for road network costs. A simple two road network (consisting of Road A and Road B) was utilized throughout this discussion. The sample network is shown in Figure 3.1.

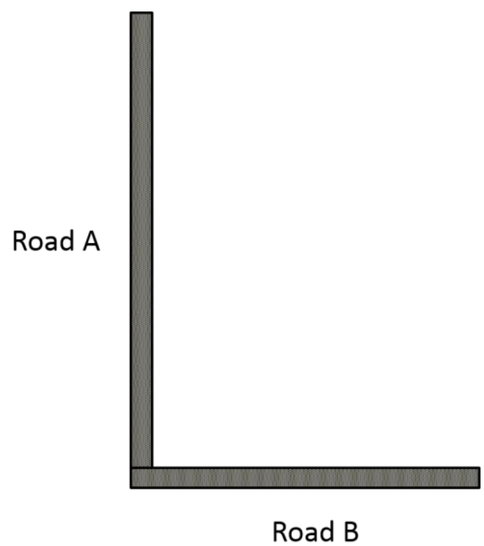

Figure 3.1: Example Two Road Network

Assume that the decision maker is trying to determine the total LCCs of managing this network. First consider the annual costs of an individual segment for any specified year, this is represented by C(i,t). These segment costs could be calculated based on the roads annual operating and maintenance costs and the required rehabilitations in the given year (t). For this example it was assumed that segment rehabilitations were only driven by a rainfall event[3]. This cost calculation is shown as a deterministic equation, meaning each variable can be assigned an expected value, in Equation 1.

Where: i - index of the road segments (i.e. Road A, Road B)

t – variable for the time in years (e.g. 0,1,2,3..)

a(i) – coefficient for the length of the segment (km)

X(i) – variable for the unit annual operating and maintenance cost ($/km)

b(i) – coefficient for the rehabilitation cost of a segment given the occurrence of a rainfall event ($)

Y(t) – variable for the occurrence of a rainfall event in a given year, t

$$\begin{cases} 1, rainfall\ event\ occurs\ in\ year\ t \\ 0,\ rainfall\ event\ does\ not\ occur\ in\ year\ t \end{cases}$$

$$C(i,t) = a(i)X(i) + b(i)Y(t) \qquad [1]$$

For the calculation of the road segment costs shown in Equation 1, there are coefficients (constants) and both local and network variables. The constant coefficients are the lengths of the segments, a(i), and the rehabilitation costs, b(i), given the occurrence of a rainfall event, these are assigned certain values. The local variables of a single segment (e.g. Road A) do not impact the local variables of other segments (e.g. Road B). The local variable in this example is the unit operating and maintenance cost, X(i). There is also a network variable (i.e. the occurrence of a rainfall event in a given year) that impacted both of the road segments, although not necessarily equally. An illustrative example of the impact of the rainfall event is shown in Figure 3.2.

[3] This assumption was made for simplification purposes. By including the renewals required at the end of the useful life, this example would become more complex. This does not necessarily represent the life cycle costs experienced with infrastructure as this example is for illustrative purposes only.

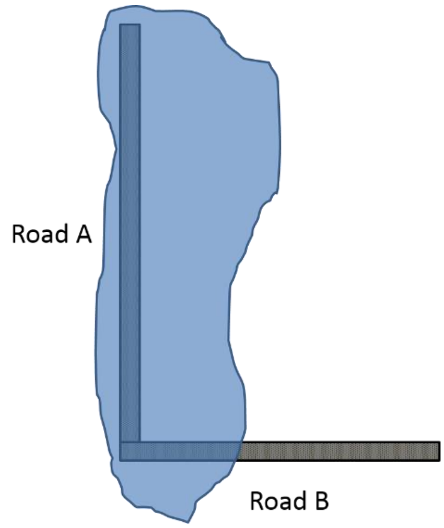

Figure 3.2: Impact of Rainfall Event on Two Road Network

If the costs of each of the network segments (i.e. Road A and Road B) are defined, then these can be summed together to calculate the network costs for a given year. The formula for the total network costs is shown in Equation 2.

$$C(t) = C(A,t) + C(B,t) = a(A)X(A) + a(B)X(B) + [b(A) + b(B)] * Y(t) \qquad 2$$

Both Equation 1 and Equation 2 have illustrated costs that were impacted by a network variable that represented the occurrence of an event (i.e. whether or not a rainfall event occurs in year t). An event is the occurrence of a set of conditions, or simply put, something happening. There can be more than one event that needs to be considered for a network. In this example, in any given year the organization may, or may not, experience a rainfall event. As well, for any given segment within the network the organization may experience a low, nominal, or high set of annual operating and maintenance costs. The method used for calculation at this point is deterministic, however the uncertainty associated with the different events are reflected in the potential event outcomes. By reviewing the potential event outcomes, the sensitivity of the network cost to the uncertainty in the input variables was demonstrated.

The defined constant coefficients and local variable (i.e. unit operating and maintenance costs) are illustrated in Table 3.1.

Table 3.1: Coefficients and Local Variable Values

	Coefficient for Segment Length (km)	**Coefficient for Rehabilitation Cost Given Rainfall Event ($)**	**Local Variable for Unit Annual Operating and Maintenance Cost ($/km)**
	a(i)	b(i)	X(i)
Road A	2	$10,000	$\begin{cases} \$1{,}000\ per\ km\ for\ event\ 'low' \\ \$1{,}500\ per\ km\ for\ event\ 'nominal' \\ \$2{,}500\ per\ km\ for\ event\ \ 'high' \end{cases}$
Road B	1	$4,000	$\begin{cases} \$500\ per\ km\ for\ event\ 'low' \\ \$800\ per\ km\ for\ event\ 'nominal' \\ \$1{,}100\ per\ km\ for\ event\ \ 'high' \end{cases}$

The occurrence of the rainfall event and the magnitude of the unit annual operating and maintenance costs are not dependent on each other. Meaning that if a rainfall event were to occur, there would be no influence on the magnitude of the annual operating and maintenance costs, and vice versa. Since there are multiple events that can occur, there are a number of combinations of potential event outcomes. Each of these event outcomes are for a single year (t) and would have to be repeated over the selected planning horizon. The potential event outcomes for a single road segment (Road A) are illustrated using a tree in Figure 3.3.

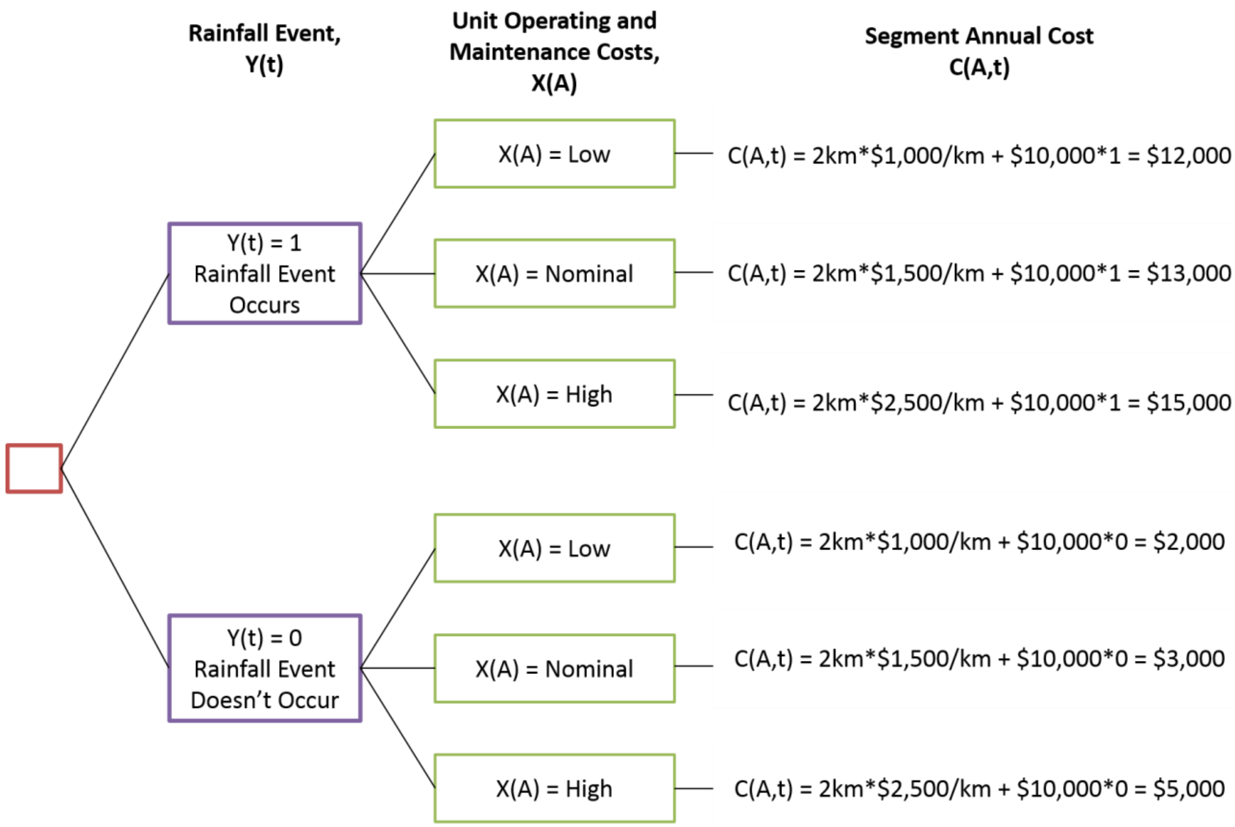

Figure 3.3: Illustrative Tree of Event Outcomes for Road A

Through the analysis of these potential events it becomes apparent that the event outcome (i.e. the network cost) is sensitive to the occurrence of the events since the network costs use these variables as inputs. In analyzing the potential events illustrated on the tree in Figure 3.3 it can be determined that there are eighteen mutually exclusive events that can occur for any given year (t). A few examples of the eighteen mutually exclusive events are: (1) [Y(t) = 0, X(A) = 'Low', X(B) = 'Low'], (2) [Y(t) = 1, X(A) = 'Low', X(B) = 'High'], (3) [Y(t) = 0, X(A) = 'Nominal', Y(B) = 'Low']. The full illustrative tree with all events and potential event outcomes is shown in Figure 3.4.

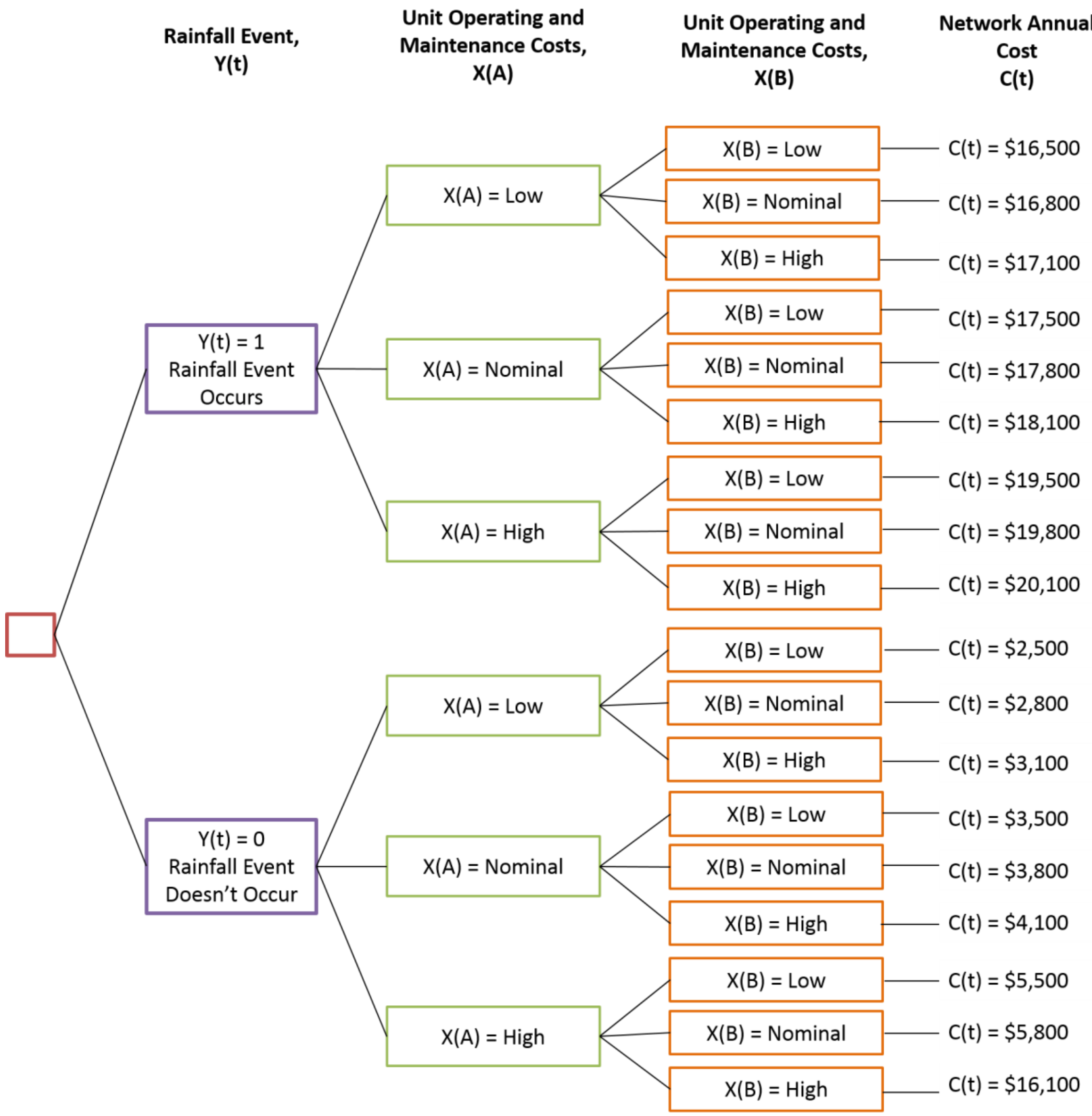

Figure 3.4: Illustrative Tree of Event Outcomes for Road Network

With the variable values defined, the event outcome (i.e. network cost) for each of the eighteen mutually exclusive events was calculated. At this point risk becomes a part of the discussion in the analysis of the network. Risk is essentially a probability concept. While risk is often discussed with a negative connotation it is better described as either a positive, negative or a result other that what was expected (AIRMIC, et.al, 2010). The risk represents the potential event outcomes considering the probability of occurrence. To be able to measure risk in the analysis of the two road network it is necessary to include the probability of the events occurring. The probability for each of the events occurring is defined (where p[X(i)] and p[Y(t)] are the probabilities of the events occurring) in Table 3.2.

Table 3.2: Event State with Associated Probability

Event State	**Probability**
p[X(i) = 'Low']	30%
p[X(i) = 'Nominal']	40%
p[X(i) = 'High']	30%
p[Y(t) = 'rainstorm event occurs' = 1]	1%, for any given year
p[Y(t) = 'rainstorm event doesn't occur' = 0]	99%, for any given year

These event state probabilities can be added to the tree that was used earlier for illustrating the potential event outcomes. This tree, including probabilities is shown in Figure 3.5. With the variable values and the probabilities defined, the event outcome (i.e. network cost) for each of the eighteen mutually exclusive events were analyzed. These probabilities and event outcomes were multiplied together and summed to give the expected value of the distribution of costs. For the decision tree shown in Figure 3.5 the expected value was calculated as $4,240 for a given year (t). The probability distribution was then graphed by comparing the event outcomes (network cost) and the probability of occurrence for each of the mutually exclusive events. The probability distribution is shown in Figure 3.6.

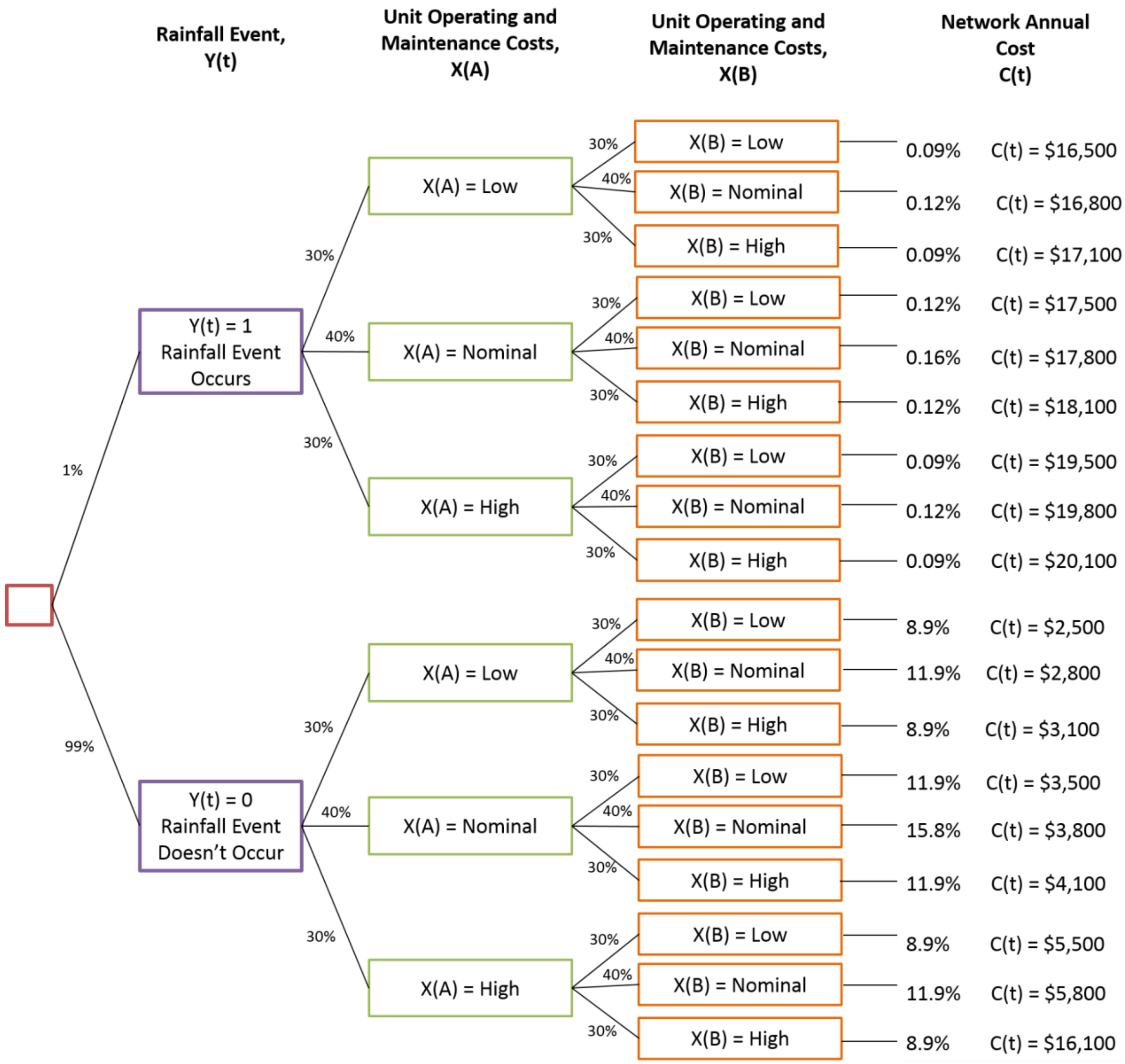

Figure 3.5: Decision Tree with Event Outcomes and Probabilities

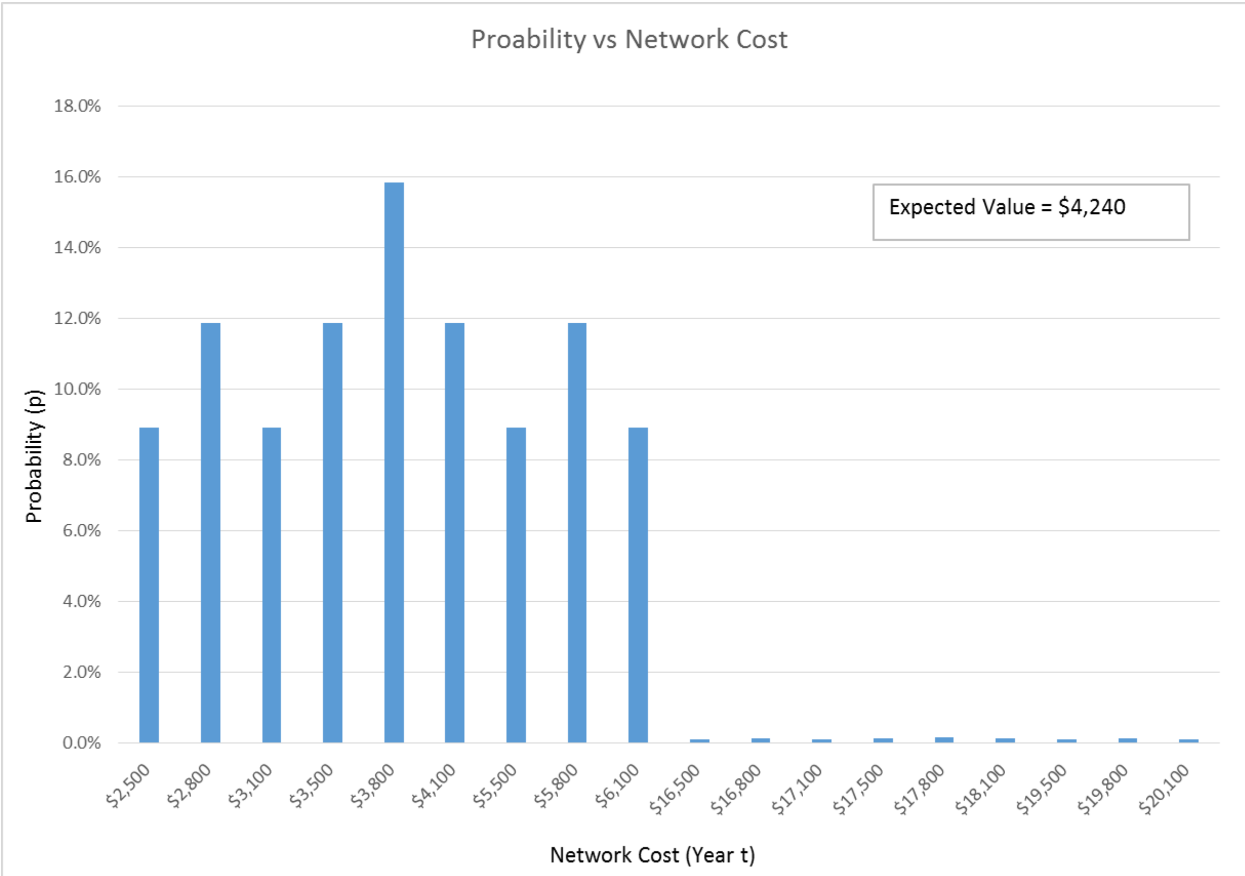

Figure 3.6: Probability Distribution

The probability distribution plot can be used to illustrate the risk associated with the potential event outcomes. At the top end there is the risk of event outcomes resulting in high network costs. At the low end there is the risk of event outcomes resulting in low network costs. Since there are probabilities associated with the event outcomes, then the expected cost ($4,240) can be calculated. By defining the event outcomes and the associated probabilities this information can also be analyzed in the form of a risk curve. A risk curve is a plot of the cumulative probability and the event outcome (network cost). The risk curve shows the extents of the potential outcomes, along with the associated cumulative probablity. In interpreting the risk curve, a network cost can be chosen and a horizontal line drawn to the associated cumulative proability. The cumulative probability measured means that there is an X% probability that the event outcome (network cost) is equal to or below the chosen network cost. The risk curve, shown in Figure 3.7 illustrates an example using an annual network cost, for year t, of $2,800. The probability that the network cost, for year t, would be equal to, or less than, $2,800, is 21%.

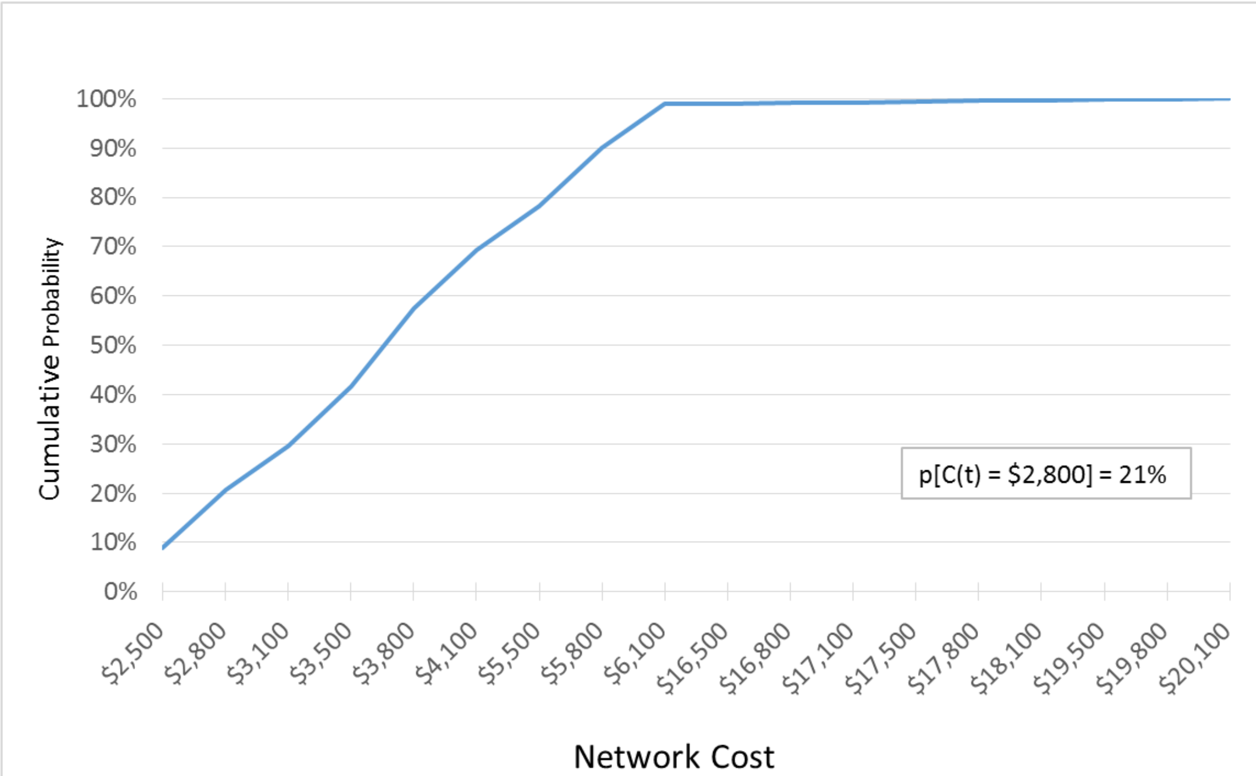

Figure 3.7: Risk Curve

Risk has been defined as not being an inherently bad thing. However, this leads to a discussion on risk attitudes. The perception of risk is dependent on the decision maker who may have either an aversion to, or a tolerance for, risk. Risk aversion leads to what has been discussed as risk management. Again, risk is not necessarily a negative thing, however, the idea of risk management has become more synonymous with the idea of removing 'bad' potential outcomes. In the literature review risk management was discussed as reducing or eliminating risk that would prove detrimental to an organization. There are really two ways to manage risk, you can (1) reduce the probability (likelihood) of the event occurring, and /or (2) you can reduce the consequences to the organization if the event does occur.

For instance in the above example if the decision was made to manage the risks associated with the rainfall event, then either the likelihood of the rainfall event occurring could be reduced or the consequences of the rainfall event could be reduced. The organization cannot influence the likelihood of the rainfall event occurring, however, there may be methods that can be used to reduce the consequences if the rainfall event does occur. Potentially, the consequences of the event may be reduced by installing a culvert to divert water away from the roads.

A critical concept within risk management is the comparison of the cost of risk management alternatives, and the potential benefits. It would not be wise to spend $10 to reduce the likelihood of an event occurring that would only cause $1 in damages. To understand the potential benefits of risk management value of information and value of control tools might be utilized. The use of value of information and value of control tools are outside the scope of this thesis. It should be noted that while the concepts and practices of risk management are important in making informed decisions, this is a vast area of knowledge that was not be discussed in detail within this research.

The purpose of this brief example was to better define the basic terms and concepts used in supporting informed decisions. Many of these concepts are discussed, and built upon, within the upcoming discussion of this research.

CHAPTER 4 DEVELOPMENT OF THE DETERMINISTIC MODEL

4.1 Introduction

The first step in completing this project was to develop a deterministic model that could estimate the LCCs of any type of infrastructure network. While this project aimed to include network variable uncertainty, it was still of utmost importance that the model established estimated the full LCCs of the network in a credible way. The purpose of first developing a deterministic model was to verify it for accuracy prior to the inclusion of network variable uncertainty within the model. As discussed earlier, when discussing the management of infrastructure it is critical that each of the three pillars are discussed: (1) level of service, (2) cost of service and (3) risk of service, as illustrated in Figure 1.1. The purpose of this research was to quantify the impacts on the network level of service and cost of service when there is network variable uncertainty stemming from potential decisions or events. This chapter discusses the development of the deterministic model to estimate the network cost of service and the associated level of service.

4.2 Network Cost of Service

In developing the deterministic model to estimate the network cost of service, a number of inputs were required. The deterministic model required inputs on network LCCs. These LCCs are based on activity type and timing over the study period. These activity costs, on a defined schedule, then have a discount rate applied to them, which results in estimates of network present worth (PW) and annual worth (AW), as illustrated in Figure 4.1. The use of network PW and AW to analyze the LCCs associated with different decisions and events was based on the wide use of these outputs for comparison and analysis purposes (USDOT, 2002).

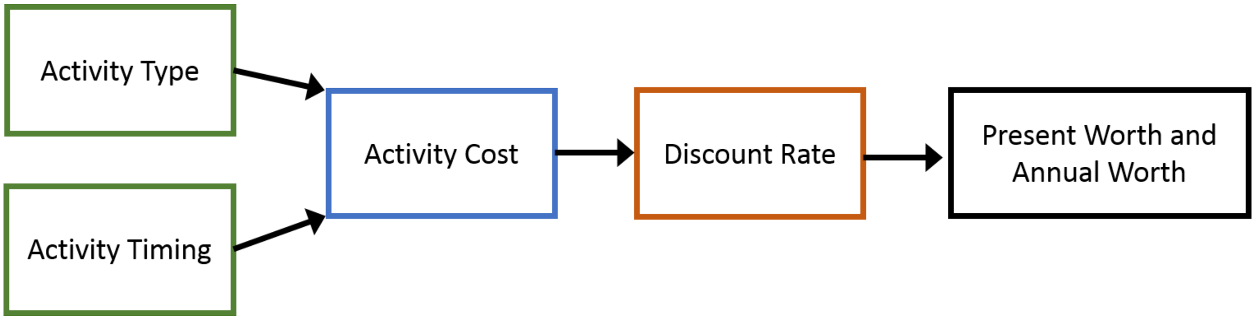

Figure 4.1: Model Inputs and Outputs

To better define the model inputs required as illustrated in Figure 4.1 it can be helpful to develop a life cycle cost (LCC) profile diagram. These diagrams define both the LCCs, in current day dollars, and the activity timing. An example of an LCC profile diagram is illustrated in Figure 4.2. Each of the bars on the LCC profile represents the magnitude of a cost at a point in time. Some of the costs are ongoing annual costs (operating and maintenance) and some are ‘one off’ or intermittent activities (capital construction and renewal). Note that the vertical axis represents costs and the horizontal axis represents time.

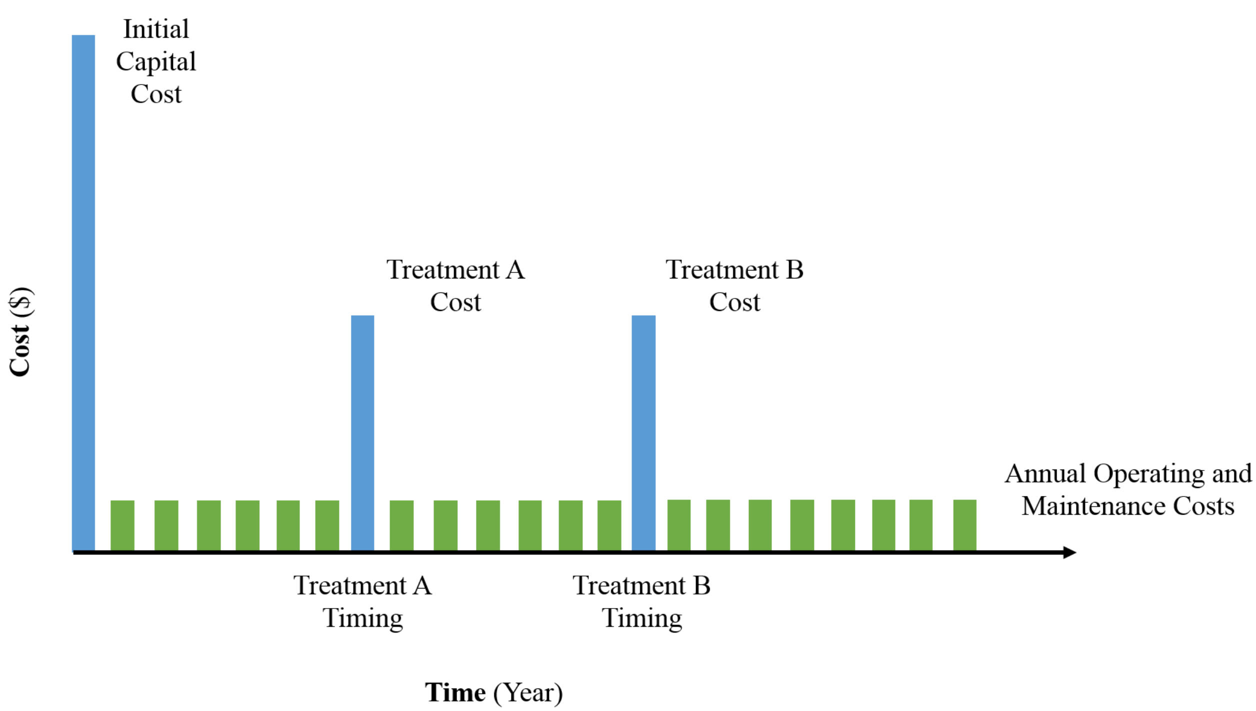

Figure 4.2: Model LCC Profile

While the LCC profile supports defining magnitude and timing of LCCs, it may be the case that the magnitude of these LCCs needs to be calculated. To calculate the magnitude of the various costs these activities were broken down to basic variables within the model to better accommodate network variable uncertainty that would later be added. The LCCs as shown in Figure 4.2 such as total capital cost, total operating cost, etc., were calculated within the model using the following formulas.

The calculation of capital costs is illustrated in Equation 3. The capital costs are the total cost of the material, labour, equipment, engineering, and design during the capital construction of the infrastructure network.

$$\begin{aligned} Capital\ Cost = {} & Cost\ of\ Materials + Cost\ of\ Labour + Cost\ of\ Equipment \\ & + Cost\ of\ Engineering + Cost\ of\ Design \end{aligned} \quad [3]$$

Once the capital costs had been calculated the operating costs were estimated. Operating activities are defined as those that do not physically impact the asset but allow the asset to provide the intended service (NAMS and IPWEA, 2011). Operating costs were calculated initially at the individual activity level (i.e. dust proofing on a gravel road) and then expanded to estimate the total of all of the operating activities.

The calculation of operating costs for an individual activity is illustrated in Equation 4. The operating costs are the total cost of the materials, labour and equipment for an operating activity carried out on the network.

$$\begin{aligned} & Cost\ of\ Operating\ Activity \\ & \quad = Cost\ of\ Materials + Cost\ of\ Labour + Cost\ of\ Equipment \end{aligned} \quad [4]$$

The calculation of total annual operating cost for the network is illustrated in Equation 5.

$$
\begin{aligned}
&Total\ Annual\ Operating\ Cost \\
&\quad = Frequency\ of\ Operating\ Activity_1 \\
&\quad \times Cost\ of\ Operating\ Activity_1 \\
&\quad + Frequency\ of\ Operating\ Activity_2 \\
&\quad \times Cost\ of\ Operating\ Activity_{2\ldots} \\
&\quad + Frequency\ of\ Operating\ Activity_n \\
&\quad \times Cost\ of\ Operating\ Activity_{n\ldots}
\end{aligned} \tag{5}
$$

Once the operating costs were established, the maintenance costs were included in the model. Maintenance activities are defined as those that allow an asset to reach its expected useful life (NAMS and IPWEA, 2011). Each individual maintenance activity cost was calculated and then summed together to estimate the total maintenance cost.

The calculation of maintenance costs for an individual activity is illustrated in Equation 6. The maintenance cost is the total cost of the materials, labour and equipment for a maintenance activity that is applied to the network.

$$
\begin{aligned}
&Cost\ of\ Maintenance\ Activity \\
&\quad = Cost\ of\ Materials + Cost\ of\ Labour + Cost\ of\ Equipment
\end{aligned} \tag{6}
$$

The calculation of total annual maintenance cost for the network is illustration in Equation 7.

$$
\begin{aligned}
&Total\ Annual\ Maintenance\ Cost \\
&\quad = Frequency\ of\ Maintenance\ Activity_1 \\
&\quad \times Cost\ of\ Maintenance\ Activity_1 \\
&\quad + Frequency\ of\ Maintenance\ Activity_2 \\
&\quad \times Cost\ of\ Maintenance\ Activity_{2\ldots} \\
&\quad + Frequency\ of\ Maintenance\ Activity_n \\
&\quad \times Cost\ of\ Maintenance\ Activity_{n\ldots}
\end{aligned} \tag{7}
$$

With the operating and maintenance costs defined the next step in setting up the model was to include renewal costs. Renewal costs are those associated with the replacement of the asset at the end of its useful life. An underlying assumption of an asset renewal is that the asset is being replaced with an asset that provides an equivalent level of service (i.e. replacing 'like with like'). Renewal is the replacement of an asset to provide a continuous existing service. As with the calculations for operating and maintenance activities, the cost of renewal is the sum of the engineering, material, labour, and equipment costs.

The calculation of renewal costs is illustrated in Equation 8. The renewal cost is the total of the materials, labour and equipment through the asset replacement.

$$\begin{aligned} &Cost\ of\ Renewal \\ &\quad = Cost\ of\ Engineering + Cost\ of\ Materials + Cost\ of\ Labour \\ &\quad + Cost\ of\ Equipment \end{aligned} \tag{8}$$

The final activity that was included in the model was disposal costs. There are points in the life cycle of an infrastructure network where there may need to be disposals of assets. Disposals may result from redundancy in the network, replacement with a new technology, or the addition of new assets. These disposals can either result in a net profit or loss to the organization. There may or may not be any disposals that need to be included in the LCCs for an infrastructure network.

The calculation of disposal costs is illustrated in Equation 9. The cost of disposal is the total of the materials, labour and equipment less the salvage value recovered in disposing of an asset.

$$\begin{aligned} &Cost\ of\ Disposal \\ &\quad = Cost\ of\ Materials + Cost\ of\ Labour + Cost\ of\ Equipment \\ &\quad - Salvage\ Value \end{aligned} \tag{9}$$

The calculations for these LCCs represent the majority of costs experienced in the management of an infrastructure network. While there may be other costs experienced in managing infrastructure, these are the ones included in this research. Any additional costs could be added as required.

Once the magnitude and timing of the costs are defined, simple engineering economic principles can be utilized to calculate the AW and the PW of the network LCCs. The AW is calculated over the life of the network, however, it is assumed to continue in perpetuity. The formula (A|P,i,n) generically refers to the annual worth equivalence depending on the: (1) present worth, (2) real interest rate, and (3) the planning period.

For capital costs the calculation of AW is illustrated in Equation 10.

Where: A – Annual Worth

P – Present Worth

i – Real Interest Rate

n – Number of Years

$$\left(A\middle|P,\ i,\ n\right) = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad [10]$$

However, if the activities associated with the LCCs do not occur at the beginning of the planning period, but rather at some point during the planning period, then the costs must first be translated into present values based on the time value of money. This is done by calculating the PW of the costs using the timing of the cost and the discount rate. For this research a real discount rate of 4%[4] was used.

The calculation of the PW of a future activity, is illustrated in Equation 11.

Where: P – Present Worth

F – Future Worth

i – Real Interest Rate

[4] A 4% Discount rate was chosen based on recent studies completed in Saskatchewan including the City of Saskatoon Planning for Growth Corridor Report (Associated Engineering, 2011) and a presentation at the TAC conference titled Updating the Saskatchewan Passing Lane Design Guide for Planning and Prioritization Purposes (Tresek, 2014)

n – Number of Years

$$\left(P\middle|F,\ i,\ n\right) = \frac{1}{(1+i)^n} \qquad [11]$$

Once the LCC of a future activity is translated to a present worth, the AW can be calculated using Equation 10. The total network AW was calculated by adding all of the AW's of the various LCCs, this is illustrated in Equation 10.

The calculation of the total AW, based on all costs is illustrated in Equation 12.

$$\begin{aligned} Total\ AW = {} & AW_{Capital\ Cost} + AW_{Operating\ Cost} + AW_{Maintenance\ Cost} \\ & + AW_{Renewal\ Cost} + AW_{Disposal\ Cost} \end{aligned} \qquad [12]$$

Finally, once the AW has been calculated the PW can be estimated using the formula illustrated in Equation 13. This particular formula was used for calculating the PW as it represents a service that will be provided in perpetuity. It is derived from the PW formula where the 'n' value is set to infinity. The PW formula shown in Equation 13 assumes that all infrastructure will be managed 'forever' this allows various alternatives with service lives to be compared over the long term.

$$PW = \frac{AW}{i} \qquad [13]$$

4.3 Levels of Service

As previously stated, when talking about the costs associated with providing services it is necessary to define what level of service is being provided for the defined cost. This is where the level of service discussion adds a critical component to the discussion of the cost of providing services.

Levels of service are an indication of the quality, function, capacity, utilization, etc. of a network. Levels of service can be measured in a variety of ways including, customer satisfaction, frequency of particular activities (i.e. grading of a gravel road), response times (i.e. hours after a snowfall event prior to snow clearing), hours of operation, and many more. The levels of service that are measured for a network are generally determined by the organization managing that network. As with the levels of service being measured, the methods for communicating levels of service for an infrastructure network vary greatly depending on the organization and the type of infrastructure that they are managing. The various guides reviewed in the research varied in how the levels of service were measured. For this research it was determined that it would be beneficial to use a method that concisely communicated the levels of service to stakeholders.

While there are an innumerable number of activities that can be considered within establishing the level of service of an infrastructure network, a few were chosen for each network considered in this research. The critical levels of service would need to be determined by the organization to establish what information needed to be communicated. The method used in this research for communicating levels of service is a dashboard method developed by the Virginia Department of Transportation (VDOT) (Cambridge Systematics , 2009). An example of how the level of service was defined in this research is shown in Figure 4.3. For the purposes of this research these dashboards were derived to represent specific activities.

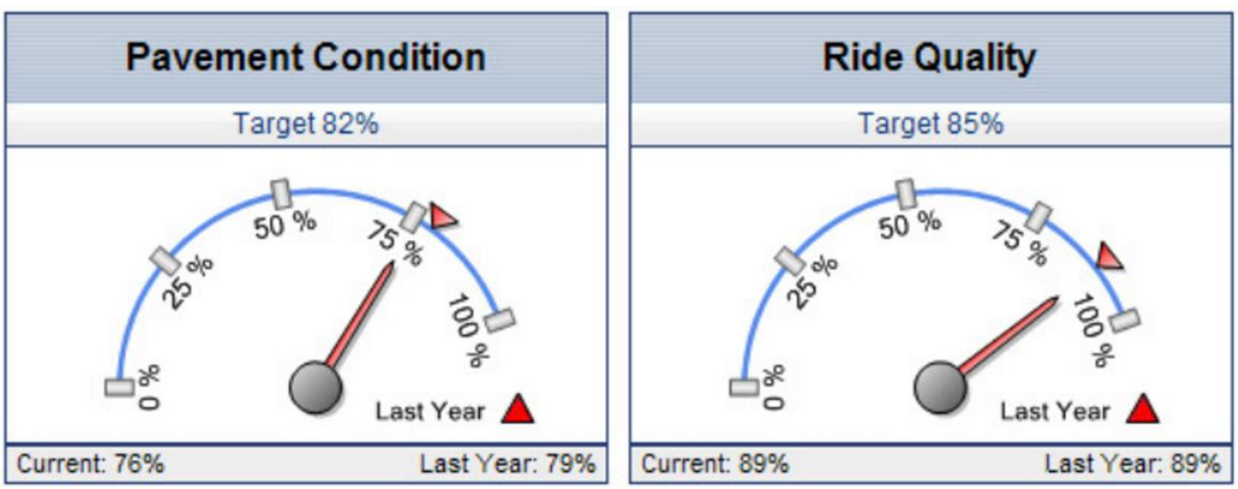

Figure 4.3: VDOT Examples of Level of Service Gauges (Cambridge Systematics , 2009)

The example of level of service illustrated in Figure 4.3 looks at the condition and ride quality level of service for a transportation department. Each of the pavement condition and ride quality levels of service are shown as a percentage, based on a scoring matrix set by the transportation department. The dashboard shows a quick highlight of the current levels of service and compares the current level of service to both a target set by the organization and the score the previous year. This method of communicating levels of service supports effective and concise sharing of information.

4.4 Summary

This chapter walked through the development of the deterministic model used in this research to estimate the cost of service. This discussion was enhanced with a discussion on how the levels of service would be communicated throughout this research. The following sections discuss the addition of network variable uncertainty to the deterministic model, as well as verification of the model, and the application of the model to case study networks.

CHAPTER 5 INCLUSION OF NETWORK VARIABLE UNCERTAINTY IN THE MODEL

5.1 Introduction

Once the PW and the AW were established within the deterministic model, the next step was to include the network variable uncertainty using probabilistic methods. This approach sought to develop a model that had the capacity to incorporate network variable uncertainty in a way that would link network costs to levels of service. Network variable uncertainty results from the occurrence of decisions and / or events. These decisions and events may impact the required costs to sustain the network and potentially alter the levels of service. This model seeks to quantify this network variable uncertainty in a credible way. By explicitly quantifying the potential event outcomes resulting from network variable uncertainty, decision makers can make informed decisions regarding the potential impacts on both costs of providing service and levels of service.

5.2 Uncertainty Events

In determining the potential impacts of decisions and events, resulting from network variable uncertainty, on network costs and levels of service, it is necessary to define the potential decisions and events that should be considered. These decisions and events need to be defined so they can be effectively communicated to increase the understanding of: (1) what is driving the network uncertainty, (2) whether or not the uncertainty results from voluntary implementation, and (3) the impacts in terms of cost and level of service to the network being managed. An example of a flowchart used to define a network variable uncertainty scenarios, based on decisions and or events, is illustrated in Figure 5.1.

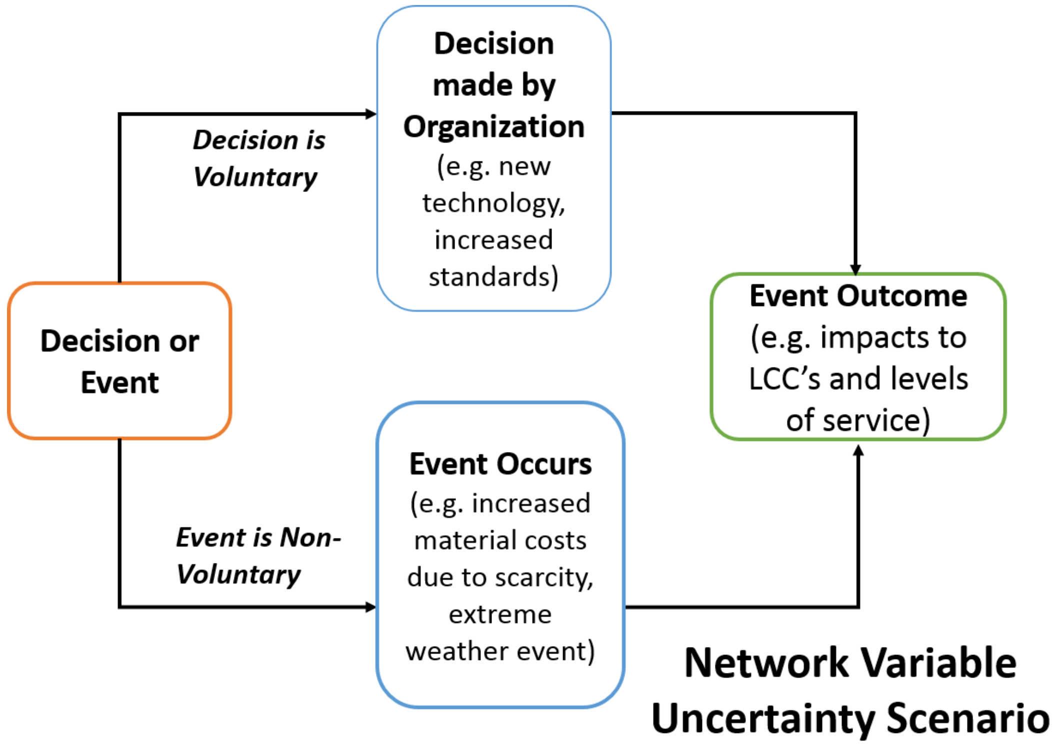

Figure 5.1: Defining Network Variable Uncertainty Scenarios

The first step in defining these uncertainty scenarios was to define what decisions or events should be considered. There are a multitude of decisions with voluntary implementation, or events with non-voluntary implementation, that could be considered. These decisions or events would be driven by the uncertainty that was most relevant for an individual organization. That being said, there are examples of decisions and events which are more frequently experienced in the management of a municipal infrastructure network. Some examples of these more frequently experienced uncertainties are: (1) changing standards, (2) changing technology, (3) increased material costs, and (4) extreme weather events. Each of these decisions or events is discussed in more detail in the following sections.

Event outcomes resulting from changing standards may come about for various reasons. This uncertainty could result through voluntary or non-voluntary implementation. An example of a voluntary decision might be the result of a resolution to increase the level of service in an organization (i.e. increased frequency in blading roads to improve road conditions). A non-voluntary event may result from governing or regulating bodies changing the current minimum standards (i.e. increased requirements for quality of potable water set by a provincial or federal government).

It would be expected that uncertainty due to changing technology would be incurred as the result of a decision. Generally speaking the reason that an organization would implement a new uncertain technology would be with the intention of decreasing costs (i.e. pipe relining instead of conventional replacement) or increasing levels of service (i.e. new road surface with possibility to have an improved surface condition over time).

Another example of an uncertainty event is increased material costs. This would be an example of a non-voluntary event. When considering the impact of increasing material costs it is important to distinguish between a normal increase in all material costs over time and a disproportionate increase in selected materials due to scarcity or other reasons. It is anticipated that over time all materials costs increase, as do other costs of living, this can be readily seen in a cursory review of the consumer price index over a period of years (Government of Canada, 2014)[5]. However, there are also disproportionate material increases which are beyond a normal cost increase. For example, gravel costs increasing at twice the rate as other materials due to scarcity. This sort of increase of one material beyond what is expected can significantly impact the management of an infrastructure network.

The final event being considered is the occurrence of an extreme weather event. Extreme weather events can result in significant impact to a part of, or all of, the network. Extreme weather events can include extreme rainfall, extreme runoff, extreme heat, etc. The uncertainty of extreme events has become more important to some organizations as in recent years they are experiencing increased frequency of extreme weather events (Rahmstorf, 2012).

5.3 Uncertainty Scenarios

Each mutually exclusive decision or event represents a scenario that needs to be considered. To fully define the network variable uncertainty as outlined in Figure 5.1 the event outcomes of the decision or event need to be quantified. Once the event outcomes of these

[5] All costs used in this model were real costs.

uncertainty scenarios are fully understood and quantified, an individual uncertainty scenario can be compared against the base case, or current status quo, of the network. The base case for this research is considered to be the current cost of providing the service and the current level of service, given the best available information, without the inclusion of network level uncertainty. In the management of an infrastructure network there may need to be several types of network uncertainty scenarios considered. To outline the various uncertainty scenarios that should be included for an infrastructure network a flowchart of various alternatives was developed, and is illustrated in Figure 5.2.

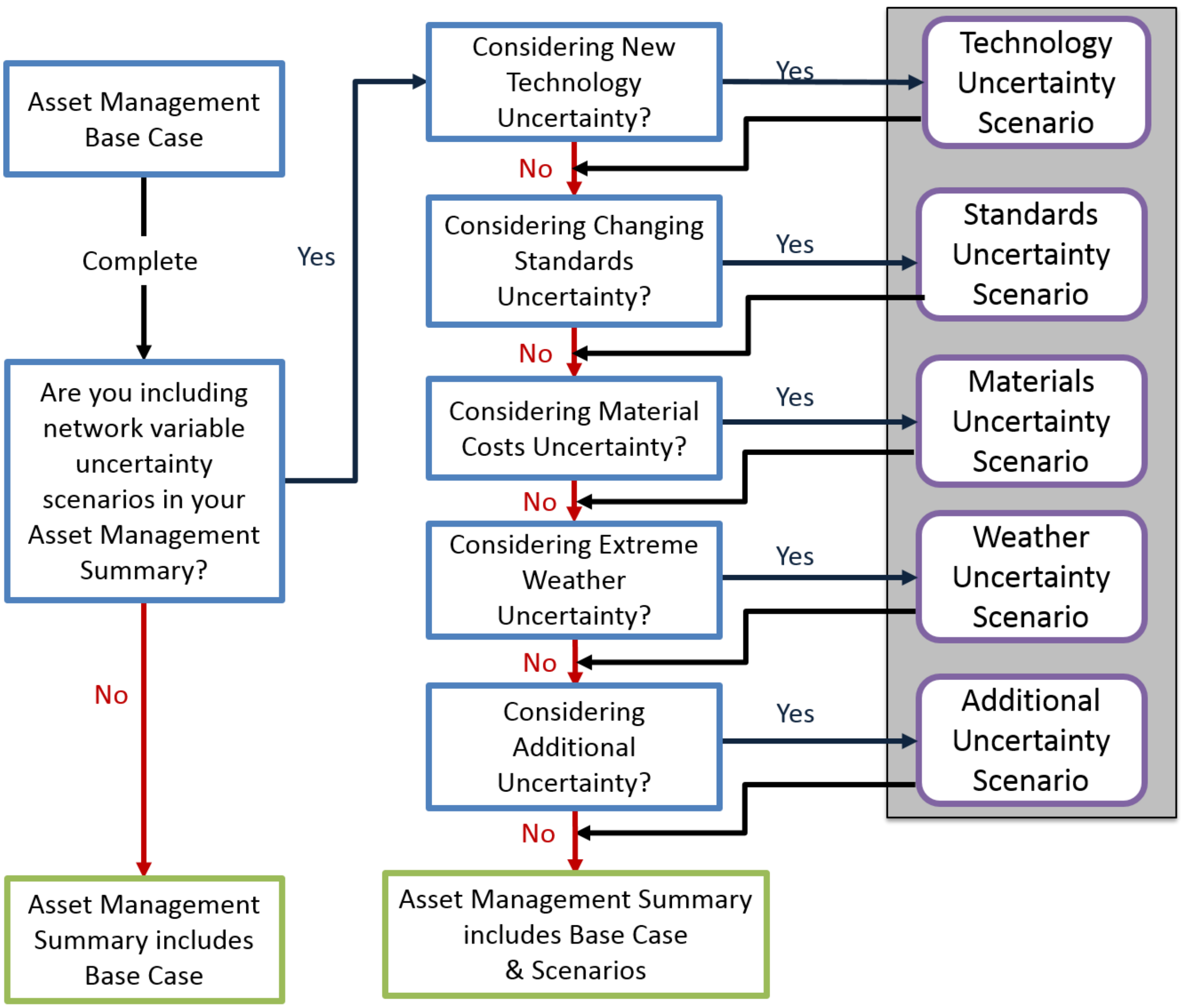

Figure 5.2: Flowchart of Various Uncertainty Scenario Alternatives

The first step in quantifying the event outcomes is to define the base case. Once the base case is understood, it needs to be determined whether or not any type of network variable uncertainty should be included. The flowchart walks through some common types of network variable uncertainties that an organization may include in their analysis. Ultimately, the final asset management summary includes the base case as well as the potential event outcomes based on the network variable uncertainty.

5.4 Flow Chart for Impact

Once an organization has outlined each of the decisions or events that should be included in the asset management summary as an uncertainty scenario, the next step is to understand the event outcomes of each of the scenarios. To facilitate the quantification of the event outcomes, a flowchart, illustrated in Figure 5.3, was developed. The flowchart walks through each of the model variables that may be impacted in terms of cost of providing service, and level of service for a specific network variable uncertainty

The flowchart illustrated in Figure 5.3 would be completed for each network variable uncertainty scenario. The various costs and activity timing that could be impacted by the decision or event, as well as the effect on the level of service, need to be considered in revisions to the base case. These updated activity timings, costs, and levels of service will quantify the potential event outcomes associated with the uncertainty scenario.

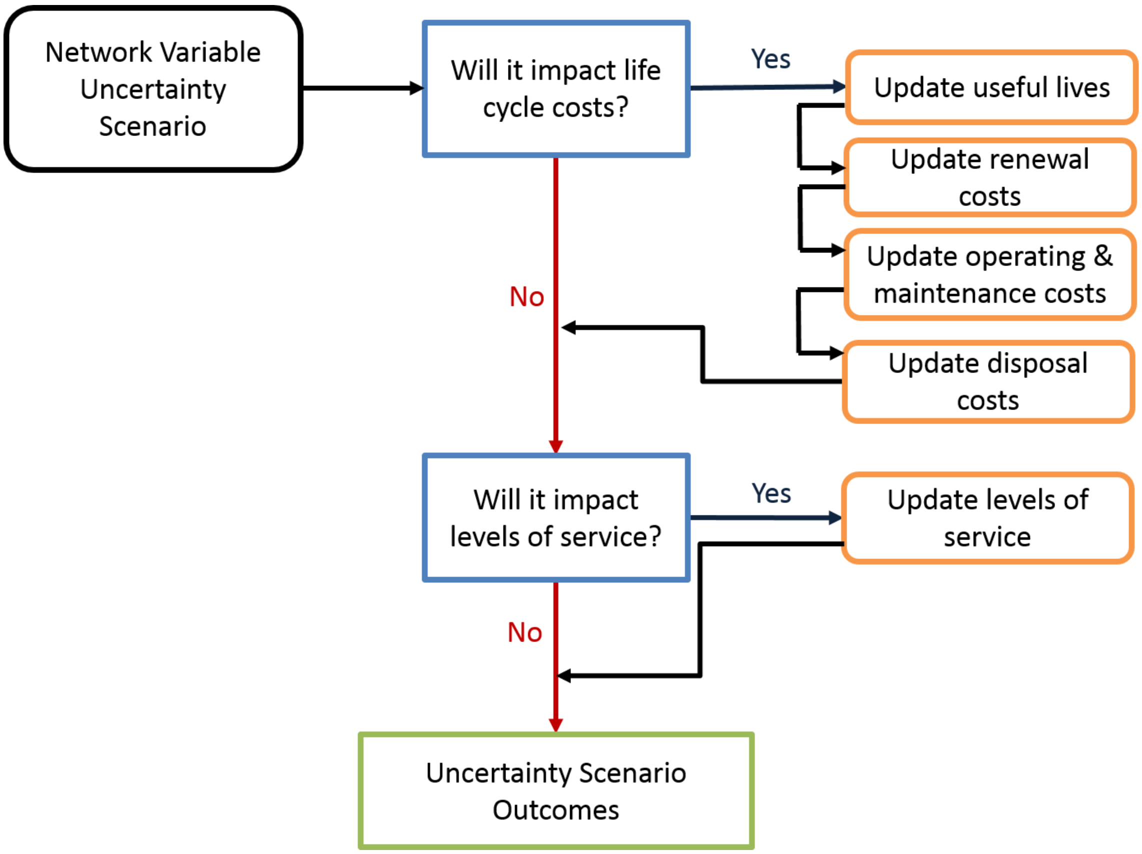

Figure 5.3: Flowchart of Outcomes of Uncertainty Scenario

5.5 Network Cost of Service Including Network Variable Uncertainty

In updating the LCCs of the deterministic model to include the decisions or events, all of the updates were based on the original formulas used in the deterministic model. Any of the variables within the calculations may be impacted by the network variable uncertainty scenario. The updated calculations, including the network variable uncertainty are shown in the following formulas, note that the subscript *UCn* represents values based on an uncertainty scenario.

The calculation of capital cost including the network variable uncertainty is illustrated in Equation 14.

$$\begin{aligned} Capital\ Cost_{UCn} \\ &= Cost\ of\ Materials_{UCn} + Cost\ of\ Labour_{UCn} \\ &+ Cost\ of\ Equipment_{UCn} + Cost\ of\ Engineering_{UCn} \\ &+ Cost\ of\ Design_{UCn} \end{aligned} \qquad [14]$$

The calculation of operating costs including the network variable uncertainty is illustrated in Equation 15.

$$\begin{aligned} Cost\ of\ Operating\ Activity_{UCn} \\ &= Cost\ of\ Materials_{UCn} + Cost\ of\ Labour_{UCn} \\ &+ Cost\ of\ Equipment_{UCn} \end{aligned} \qquad [15]$$

The calculation of total annual operating cost including the network variable uncertainty is illustrated in Equation 16. The total annual operating cost is the summation of the individual operating activities.

$$\begin{aligned} Total\ Annual\ Operating\ Cost_{UCn} \\ &= Frequency\ of\ Operating\ Activity_{1UCn} \\ &\times Cost\ of\ Operating\ Activity_{1UCn} \\ &+ Frequency\ of\ Operating\ Activity_{2UCn} \\ &\times Cost\ of\ Operating\ Activity_{2UCn} \\ &+ Frequency\ of\ Operating\ Activity_{nUCn} \\ &\times Cost\ of\ Operating\ Activity_{nUCn} \end{aligned} \qquad [16]$$

The calculation of maintenance costs including the network variable uncertainty is illustrated in Equation 17.

$$Cost\ of\ Maintenance\ Activity_{UCn} = Cost\ of\ Materials_{UCn} + Cost\ of\ Labour_{UCn} + Cost\ of\ Equipment_{UCn} \quad [17]$$

The calculation of total annual maintenance cost including the network variable uncertainty is illustrated in Equation 18. The total annual maintenance cost is the summation of the individual maintenance activities.

$$Total\ Annual\ Maintenance\ Cost_{UCn} = Frequency\ of\ Maintenance\ Activity_{1UCn} \times Cost\ of\ Maintenance\ Activity_{1UCn} + Frequency\ of\ Maintenance\ Activity_{2UCn} \times Cost\ of\ Maintenance\ Activity_{2UCn} + Frequency\ of\ Maintenance\ Activity_{nUCn} \times Cost\ of\ Maintenance\ Activity_{nUCn} \quad [18]$$

The calculation of renewal costs including the network variable uncertainty is illustrated in Equation 19.

$$Cost\ of\ Renewal_{UCn} = Cost\ of\ Engineering_{UCn} + Cost\ of\ Materials_{UCn} + Cost\ of\ Labour_{UCn} + Cost\ of\ Equipment_{UCn} \quad [19]$$

The calculation of disposal costs including the network variable uncertainty is illustrated in Equation 20.

$$Cost\ of\ Disposal_{UCn} = Cost\ of\ Materials_{UCn} + Cost\ of\ Labour_{UCn} + Cost\ of\ Equipment_{UCn} - Salvage\ Value_{UCn} \quad [20]$$

As with the deterministic model, an organization might choose to include additional LCCs. Any impact resulting from the occurrence of the decision or event would need to be considered in any additional LCCs as well.

The AW of capital costs, including network variable uncertainty, was then calculated as illustrated in Equation 21.

For capital costs the calculation of AW is illustrated in Equation 21.

$$(A|P,\ i,\ n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad [21]$$

The calculation of the total AW, including network variable uncertainty, based on all costs is illustrated in Equation 22.

$$Total\ AW_{UCn} = AW_{Capital\ CostUCn} + AW_{Operating\ CostUCn} + AW_{Maintenance\ CostUCn} + AW_{Renewal\ CostUCn} + AW_{Disposal\ CostUCn} \quad [22]$$

Finally, once the AW was calculated, the PW including network variable uncertainty was estimated using the formula illustrated in Equation 23.

$$PW_{UCn} = \frac{AW_{UCn}}{i} \quad [23]$$

The network AW_{UCn} and the PW_{UCn} represent the event outcomes of the uncertainty scenarios summarized for the network. The next step was to analyze the potential event outcomes in comparison to the base case results (the network AW and PW not including network variable uncertainty).

5.6 Introduction to Decision Programming Language

Decision Programming Language (DPL) is a decision support software that integrates with Microsoft Excel. Decision analysis is a method that is used to support improved decision making. Decision analysis assists in quantifying the uncertainty that is included in decision making and comparing outcomes of various alternatives by probabilistically modelling results. DPL probabilistic outputs include influence diagrams, decision trees, sensitivity tornado plots and risk curves (Syncopation Software, 2014). DPL was used in this research to probabilistically review the event outcomes (in terms of network AW) based on the network variable scenarios and to analyze and review these results in comparison to the base case.

In the development of a probabilistic model it is imperative to have tools that support the inclusion of uncertainty in the model. DPL assists with probabilistic modelling by having the user define the influence diagram. The influence diagram outlines the decisions and events, variables, and outputs within the model as well as the relationship between each of these. Instead of basing results on a best estimate, users include low, nominal (expected), and high values for each of the uncertainty variables. The low and high values were set as the bounds that it was expected that the data would fall within, meaning that it was unlikely that the value would lie outside of these bounds. Along with the low, nominal, and high values the user will include the probability of each of the low, nominal, or high values occurring. The DPL model is linked to an excel spreadsheet and inputs the range of potential values through the excel spreadsheet using it as a 'dummy' calculator. The DPL model then collects the outputs of the model, based on the variable probability and event outcomes, and summarizes the risk using both a sensitivity tornado plot and a risk curve.

Both sensitivity tornado plots and risk curves are important in analyzing the impact of the decisions or events on event outcomes. Tornado plots are used to measure the relative impact of the uncertainty for one variable compared to all other variables that include uncertainty. The tornado plot illustrates the range of the impact of the uncertainty of a variable on the final output of the model. This is done for each variable and then summarized in the tornado plot according to overall impact to the model outputs. This allows the user to understand the relative impact of each of the variables that includes uncertainty (examples and further explanation of tornado plots are included in subsequent chapters within this report). Risk curves illustrate the potential event outcomes of the model, along with the cumulative probability associated with that value (examples and further explanation of risk curves are included in subsequent chapters within this report).

5.7 Levels of Service Including Network Variable Uncertainty

Since level of service is a critical component of the infrastructure management discussion, it is imperative that the analysis of the impact of decisions and events is also considered in terms of the levels of service. In Section 4.3 Levels of Service, the communication method for the levels of service was discussed. This method, developed by the VDOT, was slightly modified to include the impact of network variable uncertainty. An example of a level of service for an infrastructure network is shown in Figure 5.4. In this example the network financial sustainability indicator[6] is indicated. This differs from the original level of service gauge in that both the base case (solid black line) and the network variable uncertainty (dashed lines) are included in the dashboard.

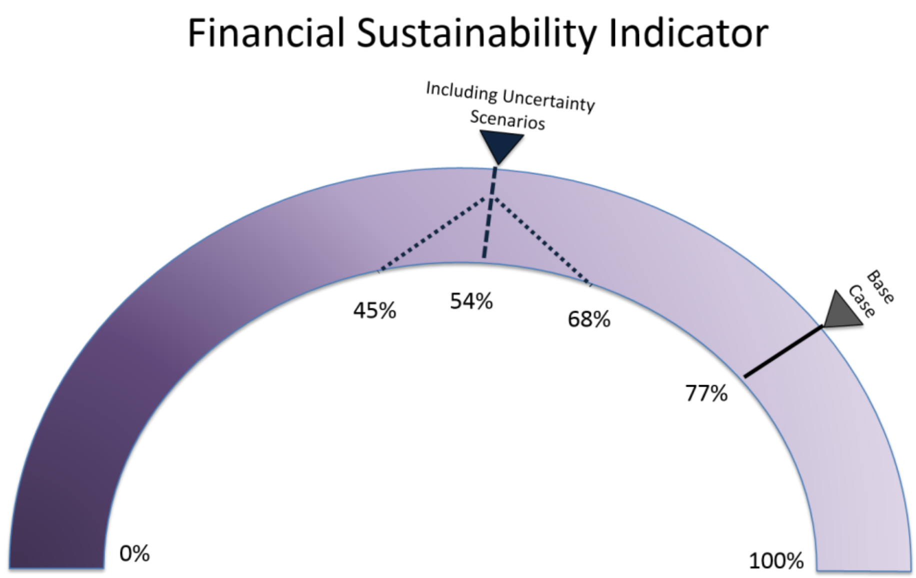

Figure 5.4: Example Level of Service Affordability

[6] Where the network financial sustainability indicator = network annual budget ($/year) / network AW ($/year)* 100%

In Figure 5.4 the network financial sustainability indicator (Annual Budget / AW) for the base case is shown as 77%. When the network variable uncertainty is included in the analysis the organization has an expected value for the network financial sustainability indicator of 54% (shown with the straight line dashed line). However, since there is uncertainty within the AW that would impact the outcome of the network financial sustainability indicator, this is represented through a triangular distribution illustrated with a dotted line. While the uncertainty distribution may not perfectly fit with a triangular distribution, it is representative of the fact that uncertainty exists within this value. The triangular distribution indicates that at the lower bound the network financial sustainability indicator is 45%, while at the upper bound the network financial sustainability indicator was estimated as 68%.

By communicating the potential impact on the network levels of service, and including the uncertainty within these values resulting from decisions and events, decision makers have more complete information. This improved information supports the discussion of network management in terms of LCCs and levels of service.

5.8 Summary

This chapter illustrated how the deterministic model developed in Chapter 4 was revised to include network variable uncertainty using probabilistic methods. This review of the revised model included discussions and tools that support the definition of uncertainty scenarios, as well as the quantification of the impact of decisions and events on both the cost of service provision and the impacts to levels of service. A discussion regarding the use of DPL to analyze the results of the model was also included. Once the model was adjusted to include network variable uncertainty, the next step was to apply the model to a hypothetical network which is the focus of Chapter 6.

CHAPTER 6 APPLICATION TO THE HYPOTHETICAL NETWORK

6.1 Introduction

To demonstrate the application of the developed LCC model with the inclusion of decisions and events representing network variable uncertainty, a hypothetical infrastructure network was utilized. The purpose of applying the model to a hypothetical network was to first verify the model, and second, to illustrate the steps that can be taken to employ these tools to support informed decision making.

The hypothetical network utilized for this example was a twelve segment gravel road network illustrated in Figure 6.1.

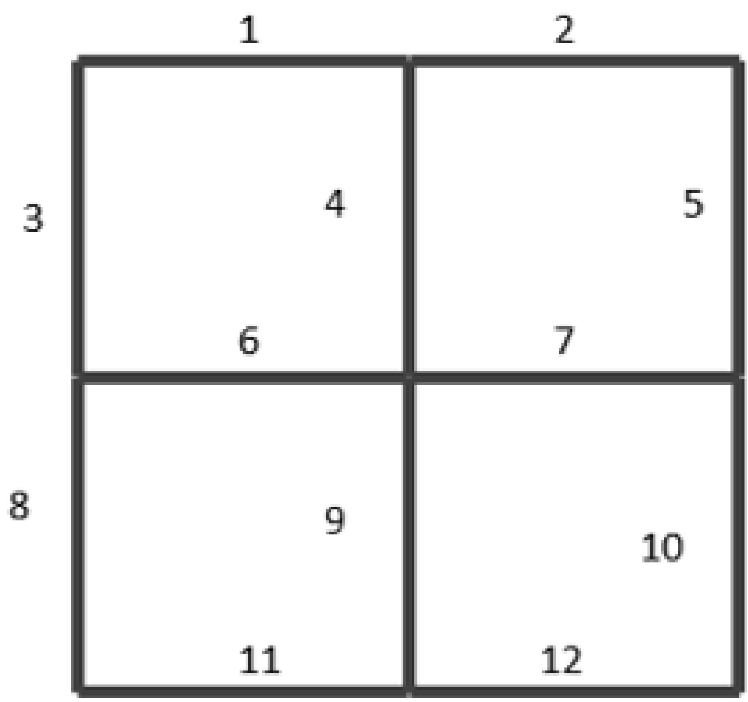

Figure 6.1: Hypothetical Road Network

Each of the twelve segments in the hypothetical network are 1 km in length. Each segment of the road network was considered to have a road structure and a gravel surface. The details of the road network are summarized in Table 6.1, for the detailed asset listing for the hypothetical network refer to Appendix B.

Table 6.1: Hypothetical Network Base Case Details

	Cost (2014 $)	Timing	Details
Road Reconstruction	$220,000 / km	Every 60 years	
Road Resurfacing	$33,000 / km	Every 5 years	Full regravelling
Clay Capping of Structure	$88,500 / km	30 years after road reconstruction	
Operations and Maintenance[7]	$21,800 / km	Annually	Includes grading, spot gravel addition, shoulder pulling, and dust control.

The information in Table 6.1 outlines the associated LCCs, in 2014 dollars, as well as the expected timing of the LCCs, other details regarding the LCCs are also included in the table. This information would likely be developed through consultation with managers and operators of the transportation network[8]. The values used in this hypothetical model are based on typical activity timing and costs developed during work with organizations tasked with managing rural road networks[9]. Once the activity costs and timing were defined, as in Table 6.1, the LCCs were calculated. An important assumption for this hypothetical network is that it was a proposed network. This means the network does not already exist and is not partway through the life cycle of some or all of the assets. The LCCs were calculated with the assumption that the entire twelve segment network would be constructed at some point in the future.

[7] For a detailed breakdown of the operating and maintenance costs refer to Appendix B.
[8] For this hypothetical network, costs provided by Saskatchewan municipalities were used for illustrative purposes only.
[9] These costs are more representative of rural roads in heavy oil areas, as they are based on information provided by communities in that particular type of region.

6.2 Base Case Life Cycle Costs

The first step in calculating the LCCs was to develop the LCC cash flow profile, this profile is shown in Figure 6.2. The cash flow profile takes the information shown in Table 6.1 and translates it to show the magnitude of the costs (vertical axis) and the timing of the activities (horizontal axis).

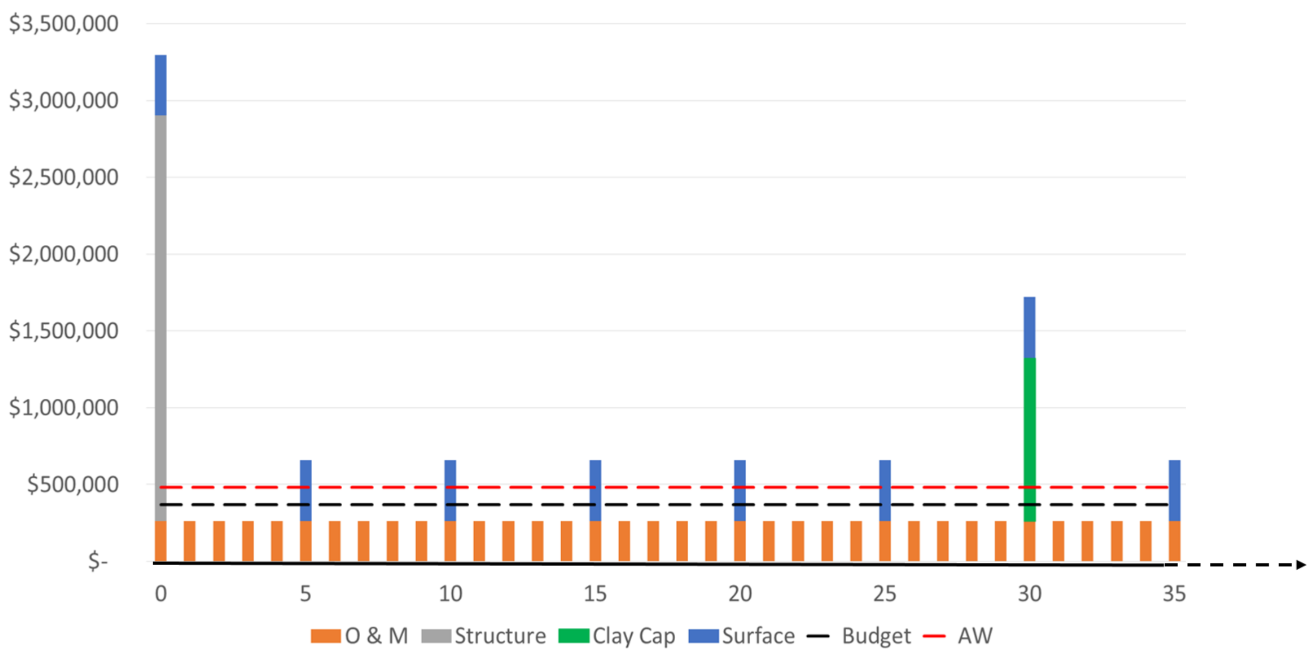

Figure 6.2: Hypothetical Network LCC Cash Flow Profile[10]

In Figure 6.2 the bars show the expected required expenditures. These bars are composed of the summation of renewal, operating, maintenance, and disposal costs, each of which are illustrated in a different color (Grey = structural replacement, Green = Clay Capping of the Structure, Blue = Resurfacing, Orange = Operations and Maintenance). There are no anticipated disposals associated with this hypothetical network. The dashed black line illustrates the current budget, while the dashed red line illustrates the projected network AW. While the LCC profile was developed for the entire 60 year study period, only the first 35 years are shown here for illustrative purposes. For an LCC profile for the full study period refer to Appendix B.

[10] The LCC cash flow profile has been truncated from 60 years to 35 years so that it is readable. The LCC cash flow profile should illustrate the longest component life cycle of the asset which for this network is 60 years. All costs shown on the LCC profile are shown in current day dollars. For the full LCC cash flow profile refer to Appendix B.

The AW and PW of the base case hypothetical network were calculated using the formulas outlined in Chapter 4. The calculated AW of the network was $481,700 and the PW was $12,043,000, these are summarized in Table 6.2.

Table 6.2: Calculation of AW and PW for Base Case Hypothetical Network

	Hypothetical Base Case Model Results
AW[11]	$481,400
PW	$12,035,700

Once the base case AW and PW were calculated the model was verified against an existing model. It should be noted that the model that was used for verification did not include any network variable uncertainty.

6.3 Verification of Model

This model was verified against an existing LCC tool called the LIRA (Land and Infrastructure Resiliency Assessment) Tool[12]. This is a tool that was developed for benefit cost analysis of various landscape adaptation options given the uncertainty of extreme weather events. The main purpose of the tool is to compare the network LCCs, using AW and PW, of various infrastructure adaptation alternatives given the impact of defined surface water runoff levels. One portion of this tool looks solely at the network LCCs including capital costs, operating and maintenance costs as well as major renewals, this part of the LIRA tool was used in isolation to verify the model developed in this research. The LIRA tool was developed for, and managed by, the Agri-Environmental Services Branch of Agriculture and Agri-Food Canada (VEMAX, 2010).

To ensure that the basic LCC estimates for the base case hypothetical network AW and the PW were correct, the values from Table 6.1 were input into the LIRA Tool and the AW and PW

[11] A 4% real discount rate and a 60 year study period were used for the calculation of AW and PW.
[12] Other tools were considered for verification including the Road Cost Knowledge System (ROCKS) developed by the World Bank and the Roads Economic Decision Model (RED). The LIRA tool was chosen as it focuses on infrastructure LCCs at the network level which best suited the developed model.

were estimated using the software tool. The results of the model verification are illustrated in Table 6.3. For additional details on the model verification refer to Appendix A.

Table 6.3: Verification of model using hypothetical network.

	LIRA Software Results[13]	**Hypothetical Base Case Model Results**[14]
AW[11]	$481,400	$481,400
PW	$12,035,700	$12,035,700

Both the AW and the PW from the developed model matched those from the LIRA tool (within rounding variability for PW). This verification demonstrated that the basic LCC portion of the model was correctly calculating the AW and PW of the network. Since the deterministic portion of the model had been verified using the LIRA Tool, the next step was to include the network variable uncertainty using probabilistic methods.

6.4 Defining the Hypothetical Network Uncertainty Scenarios

As outlined in Chapter 5, the first step in including network variable uncertainty for an infrastructure network was to define the decisions or events that could occur stemming from the network variable uncertainty. Defining these decision and events was based on consultation with municipal organizations as well as past experience in working with organizations managing public infrastructure. The decisions and events that were considered for the hypothetical network included the: (1) decision to introduce a new technology for reconstruction of the roads, (2) event of disproportionate increase of gravel costs due to scarcity, (3) event of increased standards due to increased traffic activity, and (4) occurrence of rainfall event damaging the network. The flowchart discussed in Figure 5.2 was utilized for the hypothetical network and is illustrated in Figure 6.3.

[13] An underlying assumption of the LIRA model is that infrastructure, and services, are provided in perpetuity.
[14] As discussed in Chapter 4 the PW calculation for the model developed in this research assumes that the service is provided in perpetuity.

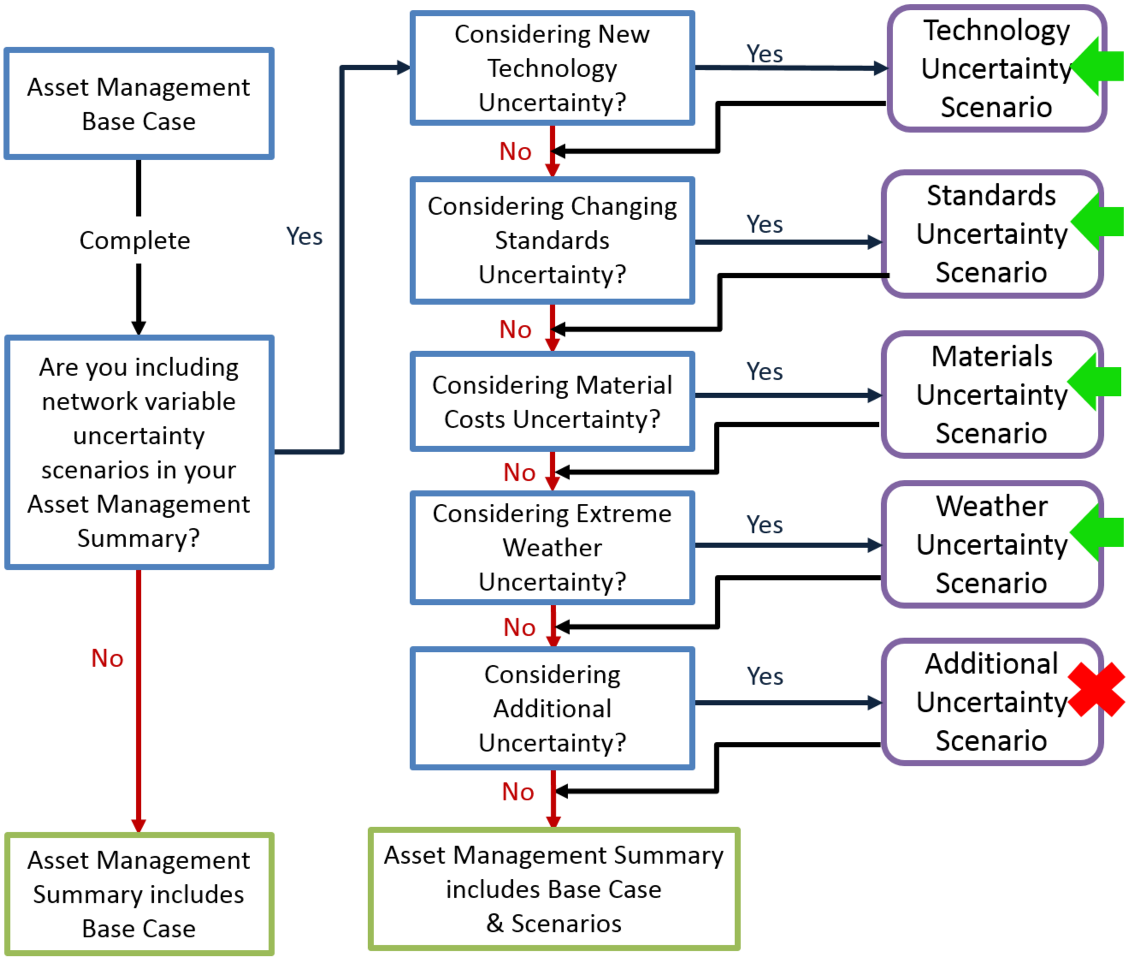

Figure 6.3: Flowchart of Uncertainty Scenario Alternatives for Hypothetical Network

As illustrated in Figure 6.3 for the hypothetical network there were network variable uncertainty scenarios considered for; (1) Technology Uncertainty, (2) Standards Uncertainty, (3) Materials Uncertainty, and (4) Weather Uncertainty. As such, the asset management summary would include the base case as well as these four additional uncertainty scenarios. Each of these scenarios is discussed in further detail within this chapter.

6.4.1 New Technology Uncertainty Scenario

A new technology uncertainty scenario was included for the hypothetical network. For illustrative purposes it was assumed that there was a potential decision for the organization to introduce a new technology that would reduce the cost of the road structure reconstruction but that also may, or may not, shorten the expected life of the road structure (shorten the time between reconstructions). This example of a potential decision to implement a new technology is an illustrative example. In reality it could be used to better inform decisions regarding potential implementation of new or unproven technologies in managing infrastructure networks. Using the uncertainty scenario flowchart the event outcomes, impacts to network LCCs and levels of service, were identified, this is illustrated in Figure 6.4.

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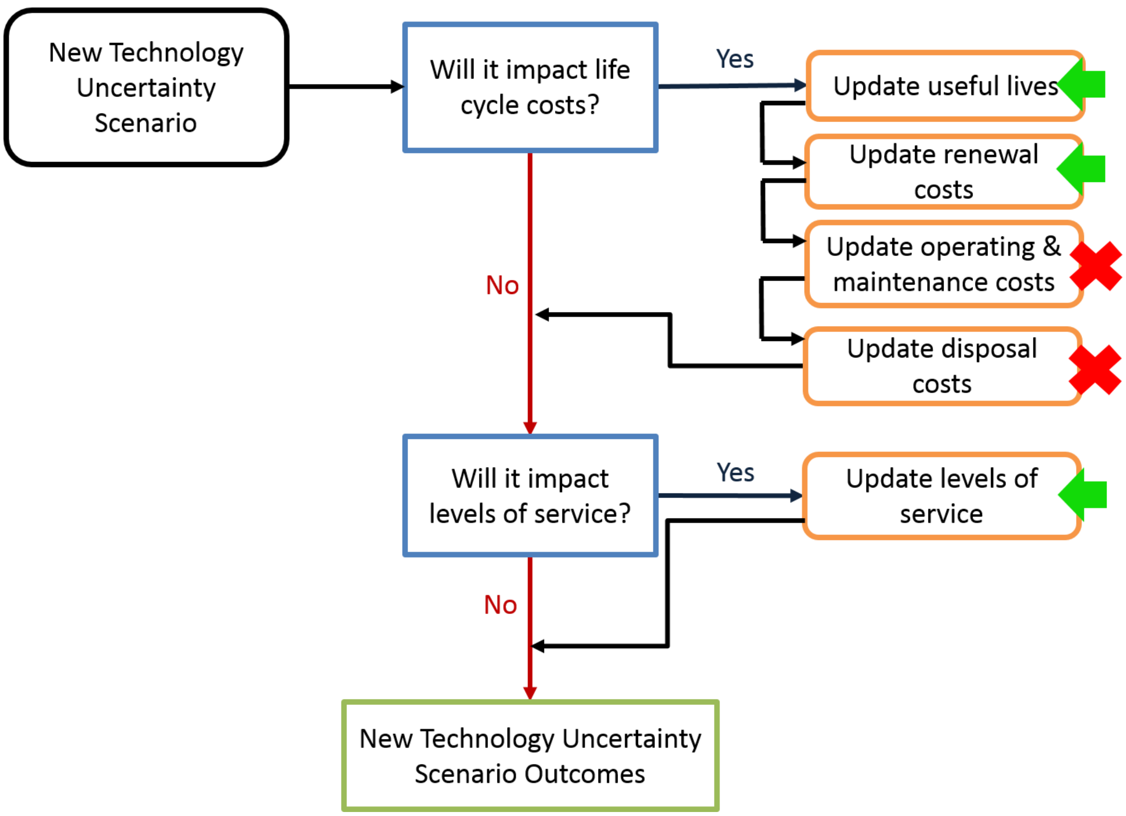

Figure 6.4: Flowchart of New Technology Uncertainty Scenario for Hypothetical Network

The purpose of the flowchart illustrated in Figure 6.4 is to illustrate how an uncertainty scenario, such as the decision to introduce a new technology would impact the potential outcomes of the LCCs, and levels of service, for the hypothetical network. Using the flowchart, it was determined that the expected useful lives, the renewal costs, and the level of service of the network, would all be impacted by this network variable uncertainty (these are indicated with a green arrow in Figure 6.4), while the operating and maintenance costs, and the disposal costs would not be impacted by the uncertainty scenario (indicated with a red 'X' in Figure 6.4). This hypothetical new technology is expected to lower renewal costs by 15%-25% from conventional renewal methods. There is uncertainty as to the reduction of costs as it is a new technology. The new technology may also result in a shorter expected useful life (ranging from 50 to 60 years) as it is a new type of treatment and an unproven expected asset life. Both the base case and the network variable uncertainty (based on the new technology) variables used for developing the LCCs are included in Table 6.4.

Table 6.4: Network Variable Uncertainty for Hypothetical New Technology Scenario

	Base Case		**New Technology Scenario**	
	Cost (2014 $)	**Timing**	**Cost (2014 $)**	**Timing**
Road Reconstruction	$220,000 / km	60 years	$165,000 - $187,000 / km	50-60 years
Road Resurfacing	$33,000 / km	5 years	$33,000 / km	5 years
Clay Capping of Structure	$88,500 / km	30 years after road reconstruction	$88,500 / km	30 years after road reconstruction
Operations and Maintenance	$21,800 / km	Annually	$21,800 / km	Annually

The variables discussed in Table 6.4 were incorporated with the other uncertainty variables into the model to calculate the impact of the network variable uncertainty. The lower and upper bounds of the event decision outcomes were calculated for the network AW. The lower and upper bounds represent the limits that it is unlikely that the outcome would be less than, or greater than, these values. The lower bound calculation was essentially a best case scenario (i.e. lowest reconstruction cost of $165,000/km and the longest expected useful life of 60 years). The upper bound calculation was a worst case estimate of the AW given the uncertainty scenario (i.e. highest reconstruction cost of $187,000/km and shortest useful life of 50 years). The lower and upper bounds for the decision to implement the new technology are shown in Table 6.5.

Table 6.5: AW Outcomes for Hypothetical New Technology Scenario

	AW		
	Lower Bound	**Expected Outcome**	**Upper Bound**
Base Case (without uncertainty)		$481,400	
New Technology Scenario	$452,300	$459,200	$466,500

The uncertainty of the upper and lower bounds for the implementation of the new technology impact the event outcomes (Network AW). The risk in the event outcomes is a range in network AW estimates of $14,200[15]. The decision to implement the new technology results in an expected network AW that is $22,200 less than if the new technology was not implemented. Even in the worst case (upper bound AW) it would still reduce the expected life cycle costs if the organization implemented the new technology. The decision to implement the new technology would result in a reduction in the network AW of 3-6%[16] over the decision to not implement the new technology.

6.4.2 Changing Standard Uncertainty Scenario

The second network variable uncertainty scenario that was included in the hypothetical example was the event of changing standards. This event would result from increased usage requiring increased blading frequency to maintain current surface quality. The event outcomes in terms of impacts to the LCCs and level of service was defined using the uncertainty impact flowchart, as illustrated in Figure 6.5.

[15] Risk = Upper Bound AW – Lower Bound AW = $466,500-$452,300 = $14,200.
[16] Percentage Savings or Loss $_{\text{Lower Bound}}$ = (Lower Bound AW (new technology) – Expected AW (base case)) / Expected AW (base case) *100% = (($452,300 - $481,400) / $481,400) *100% = 6%

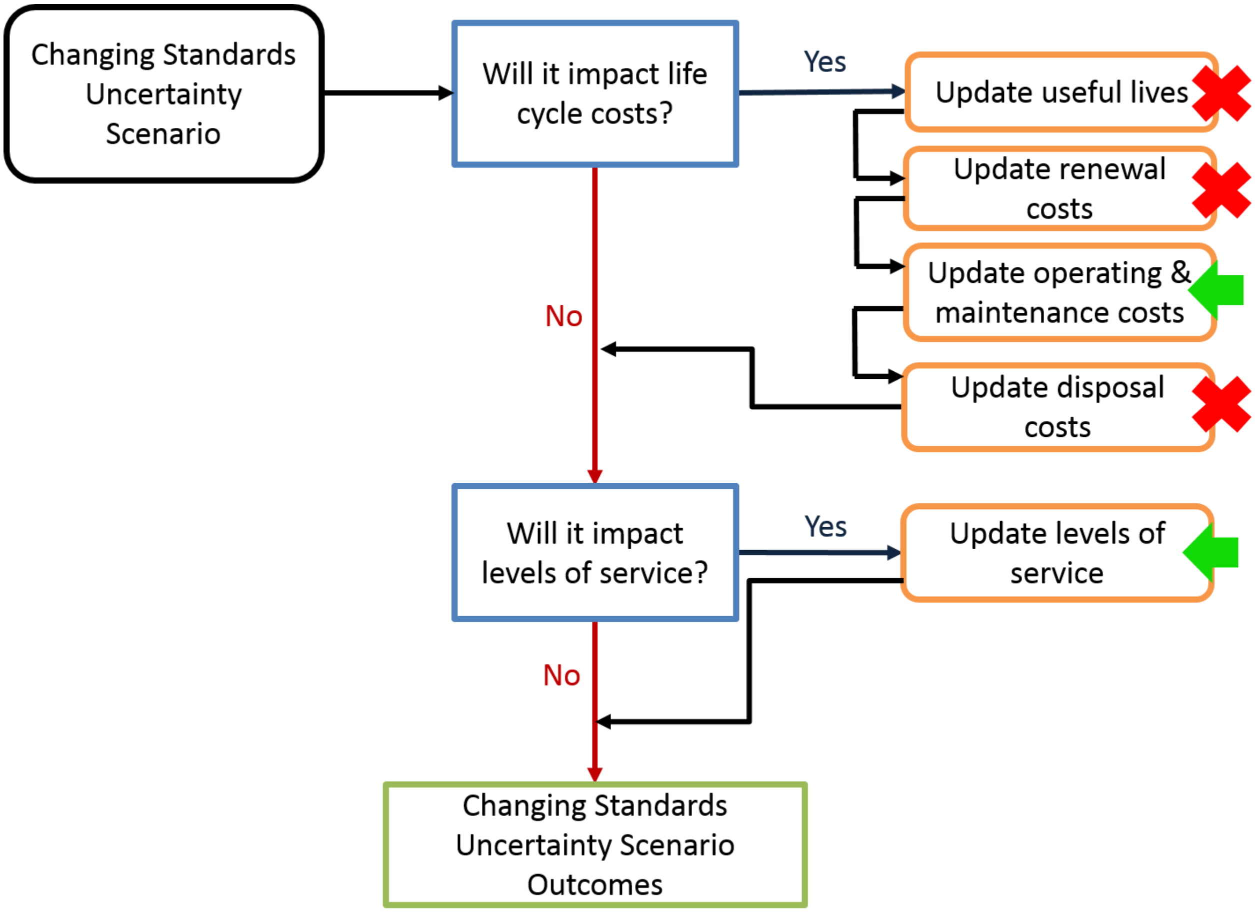

Figure 6.5: Flowchart of Changing Standards Uncertainty Scenario - Hypothetical Network

As before, the green arrows in Figure 6.5 indicate which of the variables within the calculation of the network AW would be impacted by the occurrence of this event. For illustrative purposes it was assumed that with an increased usage of the road network the required frequency of blading could range from 0-100%[17]. To increase the frequency of blading of the roads, the operating and maintenance costs within the LCCs along with the levels of service would require updating, as illustrated in Table 6.6. The useful lives, renewal costs, and disposal costs would not be impacted by this event.

[17] The increase in the frequency of blading would depend on the volume of increase and the vehicular type of the increased traffic volume.

Table 6.6: Network Variable Uncertainty for Hypothetical Changing Standards Scenario

	Base Case		Changing Standards Scenario	
	Cost (2014 $)	**Timing**	**Cost (2014 $)**	**Timing**
Road Reconstruction	$220,000 / km	Every 60 years	$220,000 / km	Every 60 years
Road Resurfacing	$33,000 / km	Every 5 years	$33,000 / km	Every 5 years
Clay Capping of Structure	$88,500 / km	30 years after road reconstruction	$88,500 / km	30 years after road reconstruction
Operations and Maintenance	$21,800 / km	Annually	$21,800 / km - $30,800	Annually

The variables discussed in Table 6.6 were used to develop upper and lower bounds for the potential event outcomes. These upper and lower bounds are again based on the limits of which the values are expected to fall within. The lower bound outcome calculation, or best case scenario, used 0% increase in the blading frequency. The upper bound calculation, or worst case scenario, of the AW used an increased frequency of 100% (i.e. doubling of the number of times annually that the roads were bladed). The lower and upper bounds for the potential outcomes of the event of increased road usage are shown in Table 6.7.

Table 6.7: AW Outcomes for Hypothetical Changing Standards Scenario

	AW		
	Lower Bound	**Expected Outcome**	**Upper Bound**
Base Case (without uncertainty)		$481,400	
Changing Standards Scenario	$481,400	$535,500	$589,600

The variability of the lower and upper bounds of the event of changing standards would result in a risk of potential event outcomes (network AW) of $108,200[18]. The expected network AW in the event of increased usage, causing an increase in standards, is $54,100 more than the expected value of the base case. If the changing standards event were to occur it is expected that the network AW would increase by 0- 22%[19].

6.4.3 Increasing Cost of Gravel Uncertainty Scenario

The third event that was considered was the increase in one particular material cost that was not consistent with other materials. It represents an increase in a material cost at a rate disproportionate to the average increase in other material costs. For this project the average increase in costs was considered to be the Non-Residential Building Construction Price Index (NRBCPI). The NRBCPI measures 'the changes in contractor's selling prices of non-residential building construction (i.e. commercial, industrial and institutional) (Government of Canada, 2014). While the NRBCPI may not perfectly reflect the actual increase in construction materials, especially the increases that have occurred in recent years in Saskatchewan, it is a better reflection than the consumer price index which is a measure of the increase in the cost of living. It is assumed that an infrastructure manager would be able to define the increase in material costs above that expected of other average increases for their particular situation. The NRBCPI across Canada increased 3.7% in 2011, 2.8% in 2012, and 0.9% in 2013. It is expected that over time the costs associated with construction will generally increase. This is illustrated by the average NRBCPI increase from 2011-2013 of 2.5%[20] (Government of Canada, 2014). The increasing cost of gravel uncertainty scenario was based on recent experience in rural RM's of escalating gravel costs due to scarcity. This has led to increased costs of the gravel itself as well as increased hauling distances which also increases the total cost. These costs have increased at an increased rate compared to most other material and construction costs. Using the uncertainty scenario flowchart, the impacts to the network LCCs and the levels of service were identified, as illustrated in Figure 6.6.

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[18] Risk in potential event outcomes = Upper Bound AW – Lower Bound AW = $589,600-$481,400 = $108,200.

[19] Percentage Savings or Loss $_{\text{Lower Bound}}$ = (Lower Bound AW (changing standards) – Expected AW (base case)) / Expected AW (base case) *100% = (($481,800 - $481,400) / $481,400) *100% = 0%

[20] The consumer price index over the same period for the province of Saskatchewan was 1.6% (Government of Canada, 2014)

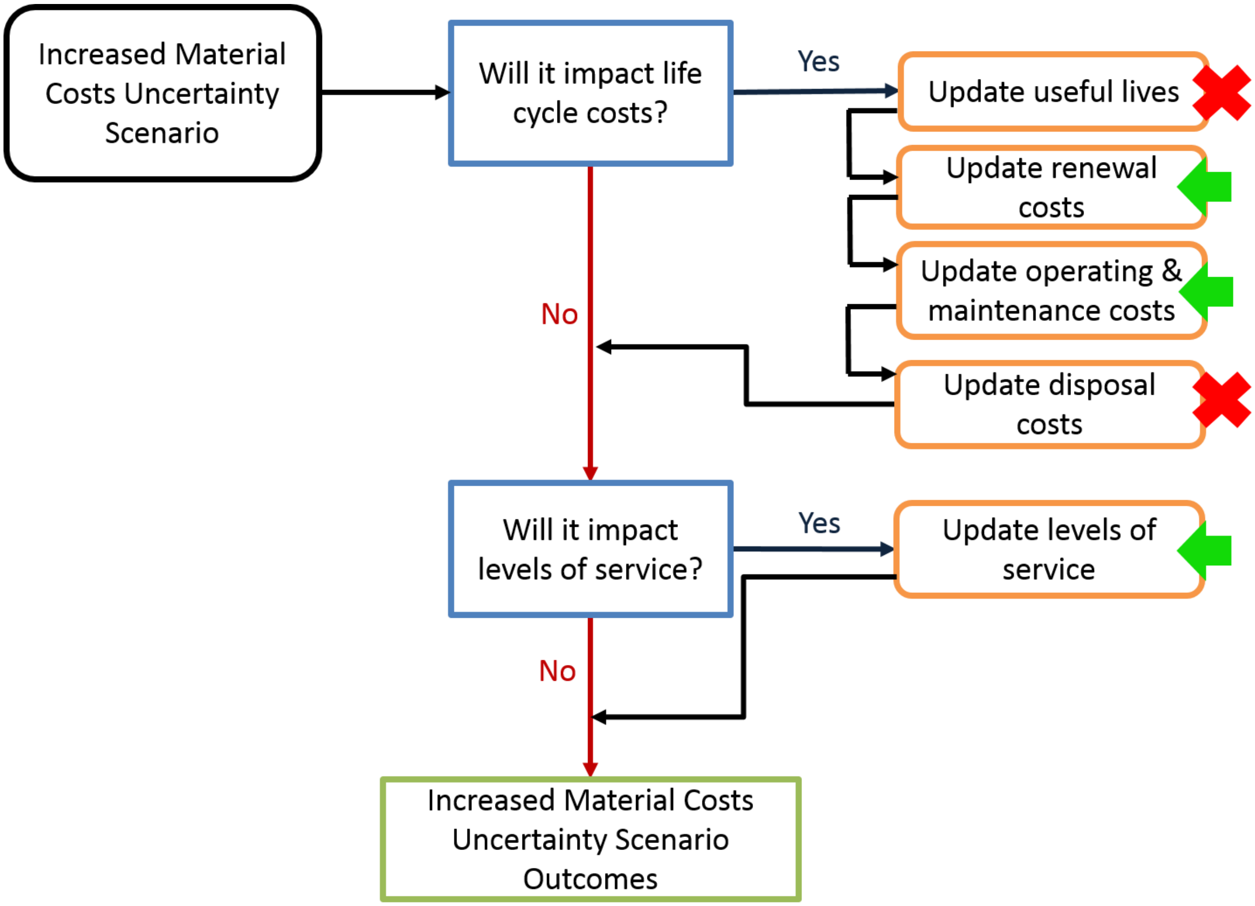

Figure 6.6: Flowchart of Increased Material Costs Scenario - Hypothetical Network

As in the analysis of the other events, the green arrows in Figure 6.6 indicate which of the variables within the calculation of the network AW would be impacted by this increasing gravel costs uncertainty scenario. The event of a disproportionate increase in gravel costs would increase the costs of any activities that require gravel. As illustrated in Figure 6.6 these cost impacts would include renewal costs, and operating and maintenance costs. As with the other events, the levels of service would also have to be reviewed. The useful lives, and the disposal costs, would not be impacted by this uncertainty scenario. For the hypothetical network it was assumed that the gravel material costs would increase by 2% - 10% per year. For this scenario it was assumed that the gravel increase would be capped at 300%[21] increase from starting year. It was determined that

[21] The sensitivity of the upper gravel increase threshold was tested. If the threshold was set at 200%, and the expected uncertainty values were used as model inputs, the output AW would be 10% less than at the

once the cost of gravel had increased by 300% it would be likely that there would be the introduction of new technology, replacement materials, or different sources. This threshold was used for illustrative purposes only, and it would be necessary for a network manager to determine this type of threshold. The impacts to LCC activities, due to the occurrence of the event of increasing gravel costs, are illustrated in Table 6.8. For more details on the hypothetical network gravel index refer to Appendix B.

Table 6.8: Network Variable Uncertainty for Hypothetical Increasing Material Costs Scenario

	Base Case		**Increasing Material Costs Scenario**	
	Cost (2014 $)	**Timing**	**Cost (2014 $)[22]**	**Timing**
Road Reconstruction	$220,000 / km	Every 60 years	$220,000 / km in 2014 gravel portion increasing by 2 – 10% per year to a maximum of 300%	Every 60 years
Road Resurfacing	$33,000 / km	Every 5 years	$33,000 / km in 2014 gravel portion increasing by 2 – 10% per year[23] to a maximum of 300%	Every 5 years
Clay Capping of Structure	$88,500 / km	30 years after road reconstruction	$88,500 / km	30 years after road reconstruction
Operations and Maintenance	$21,800 / km	Annually	$21,800 / km 2014 With gravel portion increasing by 2 – 10% per year[23] to a maximum of 300%	Annually

The variables outlined in Table 6.8 were used to develop lower and upper bounds for the event outcomes. These lower and upper bounds represent the range of expected values which it is

300% threshold. If the threshold was set at 600%, again using expected uncertainty values, the output AW would be 21% more than with the 300% threshold.

[22] These costs are representative of rural municipalities in heavy oil areas experience high traffic volumes.

[23] Above the typical material and labour cost increase.

unlikely that the values will fall outside. The lower bound event outcome, or best case scenario, used an annual increase of 2% in gravel costs per year to a maximum increase of 300%. The upper bound event outcome, or worst case scenario, calculated the network AW using an annual increase of 10% in gravel costs per year to a maximum increase of 300%. The network AW's associated with the lower and upper bounds of the event of increasing gravel costs are shown in Table 6.9. For a summary of the full indexing values used for the increase in gravel costs refer to Appendix B.

Table 6.9: AW Outcomes for Hypothetical Increasing Material Costs Scenario

	AW		
	Lower Bound	**Expected Outcome**	**Upper Bound**
Base Case (without uncertainty)		$481,400	
Increasing Material Costs Scenario	$570,200	$644,600	$685,800

The risk in the potential event outcomes, given the occurrence of the disproportionate increase in gravel costs, is the difference between the lower and upper bounds and was calculated as $115,600[24]. The expected network AW if the increase in gravel costs was to occur was $163,200 more than if the event did not occur (the base case). The occurrence of the increase in gravel material costs would be expected to increase the network AW by 18%-42%[25]. This scenario shows that an increase in the cost of gravel would have a significant impact on the network AW. It is important to note that it was necessary to cap the increase in gravel cost at a 300% increase. If the cost of gravel increased across the entirety of the planning period it would lead to exaggerated results due to the exponential increase in costs. There would be a threshold cost increase in gravel that would lead to the use of new technology, replacement materials, or the discovery of new material sources. For analysis purposes, and due to the fact that the network AW would be different each year of the study period, an average network AW over the study period was used.

[24] Risk in event outcomes = Upper Bound AW – Lower Bound AW = $685,800-$570,200 = $115,600.
[25] Percentage Savings or Loss $_{\text{Lower Bound}}$ = (Lower Bound AW (increase material costs) – Expected AW (base case)) / Expected AW (base case)*100% = (($570,200 - $481,400) / $481,400) *100% = 18%.

6.4.4 Extreme Weather Event Uncertainty Scenario

The final network variable uncertainty scenario that was included for the hypothetical network was the occurrence of an extreme weather event scenario. For this example the extreme weather event was determined to be a rainfall event. It is necessary to preface this illustrative example with the statement that what is included here is for illustrative purposes only. There is a vast field of knowledge surrounding hydrological engineering, modeling, and mapping of the impact of rainfall events on infrastructure. This level of detail is not delved into within this research. What is included here is an example of how the impacts on the network AW, due to damage caused by a significant rainfall event, is sensitive to the timing of the rainfall event relative to the age of the infrastructure. There are two types of network variable uncertainty that could be included for the analysis of the impacts of a rainfall event. First, the timing in comparison to the life cycle of the infrastructure on which the rainfall event occurs. For example, if the rainfall event occurs the year prior to a planned renewal, or the year after a planned renewal, the overall impacts to the network AW may differ significantly. This network variable uncertainty, regarding the impacts of a rainfall event relative to the assets life cycle was considered within this example. The second network variable uncertainty regarding a rainfall event is the frequency and timing of events. If an 1 in 100 year rainfall event was considered, there is a 1% probability in any year that the rainfall event would occur. This means that the rainfall event could happen in any single year, or multiple years, throughout the study period, or it may not happen at all. The frequency of the rainfall event was not considered within this research.

For this network variable uncertainty scenario it was assumed that an extreme weather event would be a rainfall event that could cause significant damage to the network. For large networks a rainfall event would be unlikely to cause consistent damage across a network, there would be areas with higher runoff which were more impacted, and areas with lower runoff that were less impacted. For this simplistic example it was assumed that each of the twelve network segments would be impacted by the rainfall event. If this model were to be applied to a real road network, damage would be estimated based on the severity of the rainfall event, and the associated implications to the infrastructure could be determined using flood mapping. However, for illustrative purposes this example will assume that given the occurrence of this rainfall event, all of the roads in the sample network would require reconstruction.

The purpose of this illustrative example was to illustrate how the timing of the rainfall event, relative to the life cycle of the infrastructure, would differently impact the network AW. Using the uncertainty scenario flowchart the impacts to the network LCCs and the levels of service were identified, as illustrated in Figure 6.7.

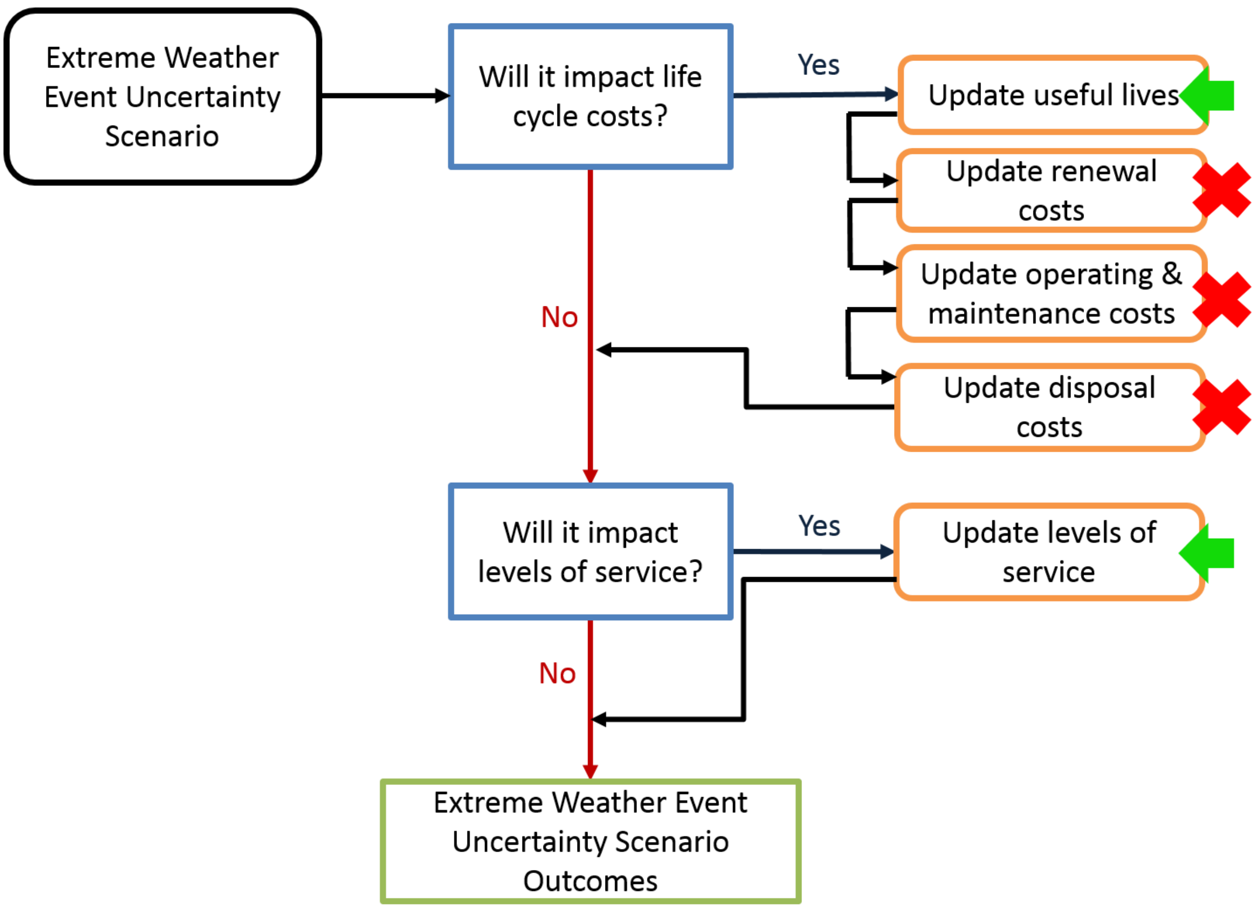

Figure 6.7: Flowchart Extreme Weather Event Uncertainty Scenario – Hypothetical Network

As in the analysis of the other events, the green arrows in Figure 6.7 indicate which of the variables within the calculation of the network AW would be impacted by the occurrence of this rainfall event. The occurrence of this rainfall event would require an unplanned reconstruction of the roads at some point during the life of the infrastructure, which would impact the expected useful life of the road infrastructure. The renewal costs, operating and maintenance costs, and disposal costs would not be impacted by this event. For the hypothetical network it was assumed that the rainfall event could occur the year after the initial construction of the road network (the worst case scenario for this simple example) or it could not occur during the study period (the best case scenario for this simple example). The impacts to LCC activities, due to the occurrence of the rainfall event are summarized in Table 6.10.

Table 6.10: Network Variable Uncertainty for Hypothetical Extreme Weather Event Scenario

	Base Case		**Extreme Weather Event Uncertainty Scenario**	
	Cost (2014 $)	**Timing**	**Cost (2014 $)**	**Timing**
Road Reconstruction	$220,000 / km	Every 60 years	$220,000 / km	Every 60 years or the year that an extreme event occurs
Road Resurfacing	$33,000 / km	Every 5 years	$33,000 / km	Every 5 years
Clay Capping of Structure	$88,500 / km	30 years after road reconstruction	$88,500 / km	30 years after road reconstruction
Operations and Maintenance	$21,800 / km	Annually	$21,800 / km	Annually

The variables outlined in Table 6.10 were used to develop lower and upper bounds for the event outcomes. The lower bound outcome, or best case scenario, assumed that the rainfall event did not occur within the study period (e.g. year 300). The upper bound event outcome, or worst case scenario, assumed that the rainfall event occurred the year after the network was constructed (i.e. year 1). The nominal value used for the occurrence of this rainfall event was year 29. The network AW associated with the lower and upper bound of the rainfall event are shown in Table 6.11.

.

Table 6.11: AW Outcomes for Extreme Weather Event Scenario

	AW		
	Lower Bound	**Expected Outcome**	**Upper Bound**
Base Case (without uncertainty)		$481,400	
Extreme Weather Event Scenario	$481,400	$493,200	$525,000

The risk in the potential event outcomes, depending on the timing of the rainfall event compared to the life cycle, is the difference between the lower and upper bound outcomes and was calculated as $43,600[26]. The expected network AW if the rainfall event occurs was $11,800 more than if the rainfall event did not occur. This shows that the occurrence of this particular rainfall event would increase the network AW by 0-9%. This simple example was used to illustrate how the timing of a damaging rainfall event would impact the network AW, but it did not look at the potential impacts of the frequency of events.

6.5 Uncertainty Scenarios Life Cycle Costs

In the previous discussion the lower and upper bound outcomes were calculated for each of the decisions and events that were driven by network variable uncertainty. A summary of the event outcomes, in terms of network AW, including expected values and all lower and upper bound outcomes are outlined in Table 6.12.

[26] Risk of potential outcomes = Upper Bound AW – Lower Bound AW = $525,000-$481,400 = $43,600.

Table 6.12: AW Results for Network Variable Uncertainty Scenarios

Decision or Event	**Base Case**	**Lower Bound**	**Expected Outcome**	**Upper Bound**
	AW	AW	AW	AW
Implement New Technology	$481,400	$452,300	$459,200	$466,500
Changing Standards	$481,400	$481,400	$535,500	$589,600
Increasing Material Costs	$481,400	$570,200	$644,600	$685,800
Extreme Weather Event	$481,400	$481,400	$493,200	$525,000

After the expected value, and lower and upper bound event outcomes had been calculated, the next step was to include all of the uncertainty in the analysis of the potential impacts to the network AW. This was done to demonstrate that various types of network variable uncertainty could be considered together to determine the potential overall impacts to the network AW. This was done by linking the excel model to DPL and assigning probabilities to the occurrence of the alternative events. The first step in establishing the DPL model was the creation of an influence model. This model illustrates the variables that are driving the event outcomes within the model. The influence model for this hypothetical network is shown in Figure 6.8. For further details on the variable estimates and associated probabilities assigned to the nodes in the influence model refer to Appendix B.

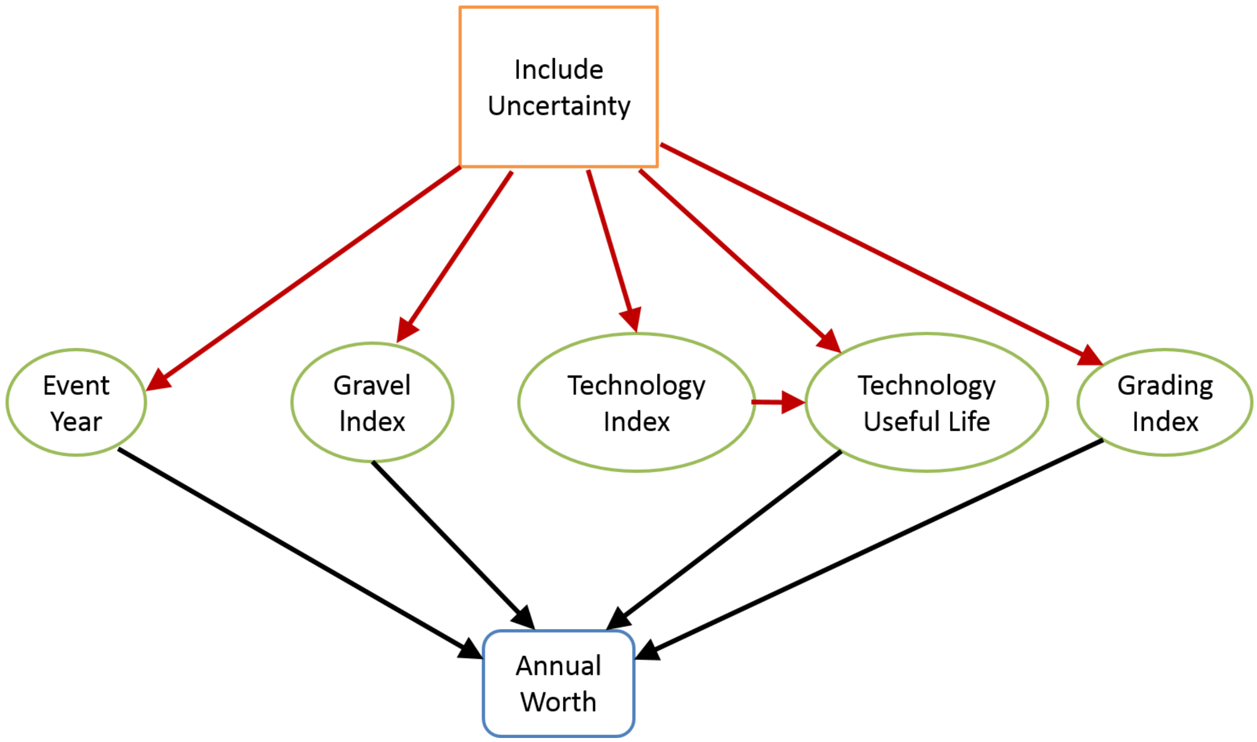

Figure 6.8: DPL Influence Model for LCCs of Hypothetical Network Uncertainty Scenarios

Each of the nodes in the influence diagram represents a decision or event, variable, or event outcome in the excel model that was driven by the DPL software. The orange box is the decision or event node. This node is represented by a yes or no value defining whether the event occurs, or the decision is made. Each of the green nodes represents an uncertain variable with multiple values and associated probabilities[27]. The blue node is the output of the model (network AW). The arrows in the influence diagram indicates the functional relationships between the nodes.

6.5.1 Hypothetical Network with Uncertainty Tornado Diagram

Once the influence diagram was developed within excel and linked to DPL the risk associated with the event outcomes were analyzed. The first DPL output that would support informed decision making is the tornado diagram. The purpose of a tornado diagram is to look at the relative significance of the uncertainty within each variable analyzed. The tornado diagram that was developed for the hypothetical network, and shown in Figure 6.9 was a base case type.

[27] Probabilities for this example were based on Swanson's 30-40-30 rule (Hurst, 2000)

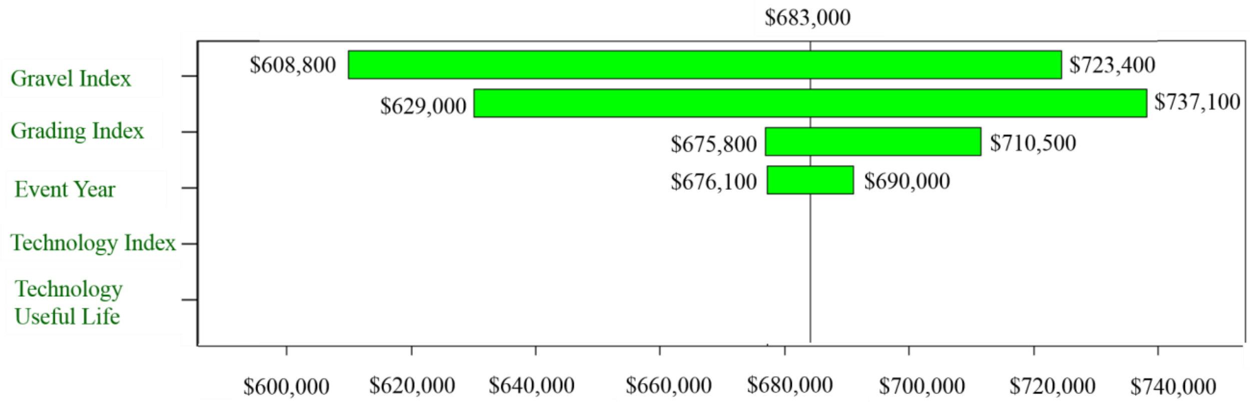

Figure 6.9: DPL Tornado Plot for Significance of Uncertainty Variables.

A base case tornado diagram first calculates the base case by running the model with each of the uncertain variables set at the expected value[28]. This base case is illustrated by the vertical black line on the diagram in Figure 6.9. For the hypothetical network the base case result was a network AW of $683,000 per year. The model was then run for each specific uncertain variable (i.e. Gravel Index) with the values of that variable set at the low and high values (for all variable values refer to Appendix B), all other variables remained set at the expected value. The variables were then graphed based on the relative impact to the model output (network AW) given the variable uncertainty. By stacking the uncertain variable with the most impact at the top in decreasing order to the uncertain variable with the least impact results in the shape of a tornado. The tornado diagram illustrates that the model output (network AW) is most sensitive to the uncertainty resulting from the increase in gravel costs (gravel index), and is not sensitive to the uncertainty in the change in expected life stemming from the implementation of a new technology.

6.5.2 Hypothetical Network with Uncertainty Risk Curve

The other important output from the DPL model is the risk curve shown in Figure 6.10. The risk curve illustrates the potential event outcomes along with the cumulative probability. The horizontal axis represents the event outcome (network AW) and the vertical axis represents the cumulative probability. If a horizontal line is drawn for any event outcome on the vertical axis, at

[28] The expected value is not equal to the value if no uncertainty was included. The expected value is the most likely value given uncertainty is to be included – three values are estimated in the DPL model for each uncertain variable, a low, nominal and high value.

the point where it intersects with the risk curve is the probability that the event outcome will be less than, or equal to, that event outcome. The risk curve for the hypothetical network with all uncertainty scenarios is shown in Figure 6.10.

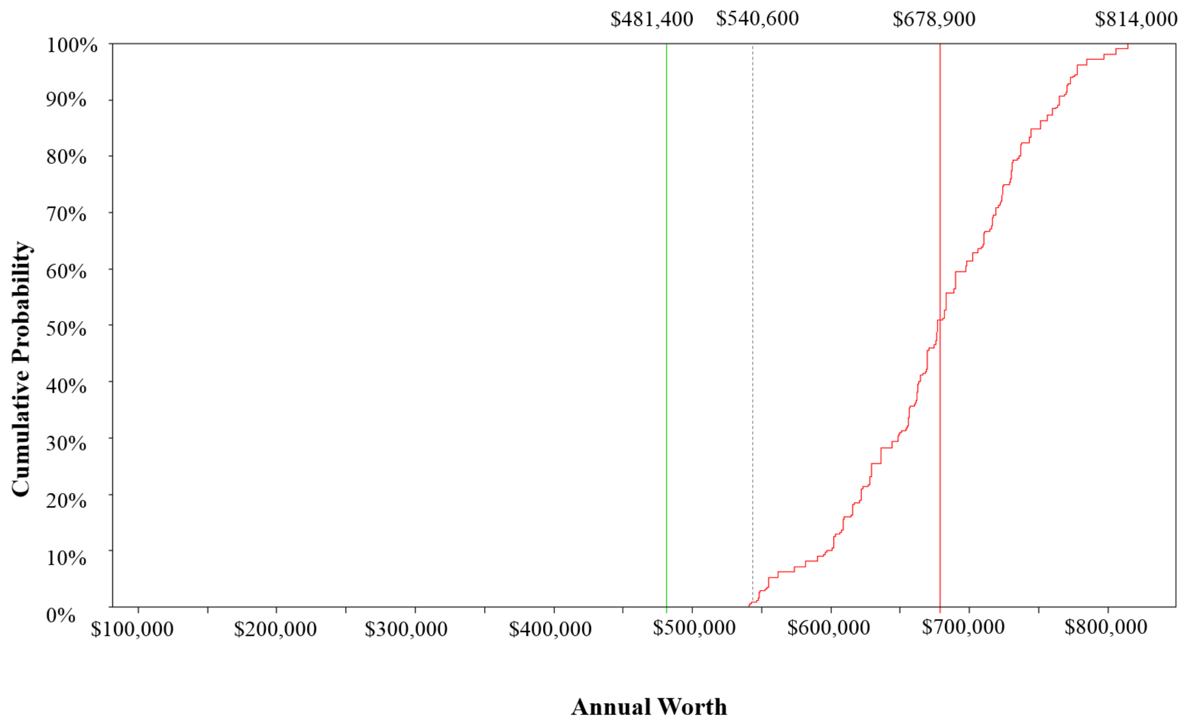

Figure 6.10: DPL Risk Curve for Hypothetical Network AW Including Uncertainty

The risk curve for the hypothetical network AW shows the expected value, given the occurrence of the events, which is indicated with the vertical line shown with a network AW value of $678,900 per year (red = yes events occur). The risk curve also indicates the expected value if the events do not occur, the base case (green = no events do not occur). This is shown as a vertical line (indicating that there is no risk) with an expected network AW of $481,400 per year. With the occurrence of these events the potential event outcomes range from a network AW of $540,600 to $814,000 per year. The risk curve illustrates that if the events occur, then the hypothetical organization would need to plan for the network AW to be increased by $197,500[29] more than if the events do not occur. With the occurrence of the events the network AW would be expected to

[29] AW (Uncertainty Events) – AW(Base Case) = $678,900 - $481,400 = $197,500

increase by 41%. The final part of the impacts to be considered due to the network variable uncertainty is the impact to the levels of service.

6.6 Levels of Service

With the network AW defined for the occurrence of the decisions and events on the hypothetical network, the next piece of information required to support informed decision making was the impact to the levels of service. The potential variability in what can be measured for levels of service has already been discussed. For the hypothetical rural road network it was determined that two levels of service would be measured. These level of service measures included the network financial sustainability indicator and the frequency of blading. The network financial sustainability indicator is a measure of the network AW in comparison to the current annual budget (network annual budget / network AW*100%). The frequency of blading is a common description used by rural municipalities to indicate how many times a week the roads are bladed, and in a particular context can be indicative of the surface condition of the roads. The base case levels of service were established first. The current network financial sustainability indicator was calculated as 77%[30]. For the hypothetical network the base case frequency of blading was every 1 in 7 days. The levels of service are shown in Figure 6.11.

The network financial sustainability indicator is a comparison of the budget and the network AW. At any point in time the measure of network financial sustainability may be appropriate even if it is not equal to 100%, as the budget is directly related to immediate expenditures required, and the network may be in a period of low renewal. If the network financial sustainability indicator is measured as a trend over time, then in the long term the budget should, on average, equal the network AW to ensure that the funds are available to manage the network, over the long term, in a sustainable way.

[30] Network Financial Sustainability Indicator = Annual Budget / AW *100% = $370,000 / $481,400 = 77%

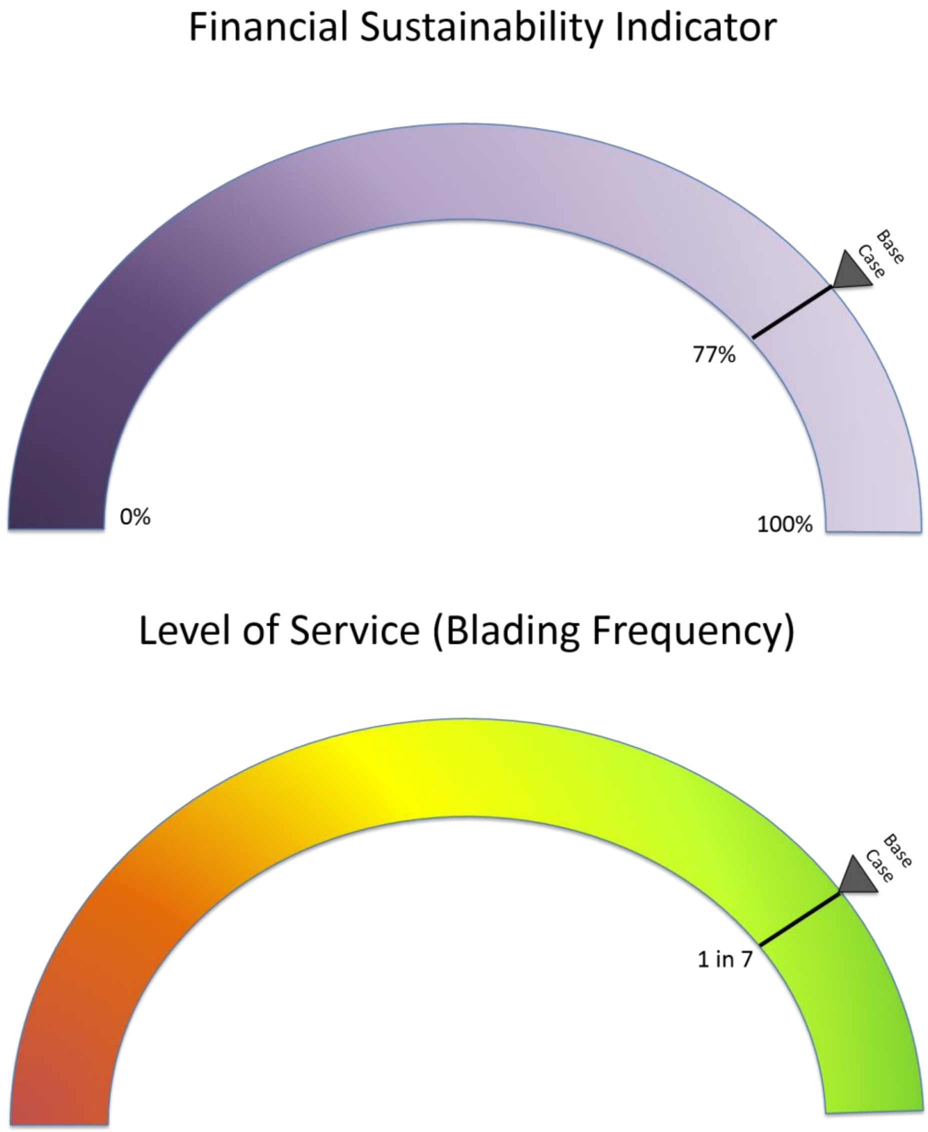

Figure 6.11: Levels of Service for Hypothetical Network Base Case

With the base case levels of service defined it was possible to compare the impact of the decisions and events on the levels of service. In the development of the event outcomes it was determined that the impact on level of service for the frequency of blading would be identified for the individual decisions or events. This would illustrate if the level of service was sensitive to some or all of the events occurring. The frequency of blading was only sensitive to the event of increased standards[31]. It is critical that any discussions regarding the potential event outcomes of the decision also include reference to the potential impacts to the levels of service. The revised levels of service are illustrated in Figure 6.12.

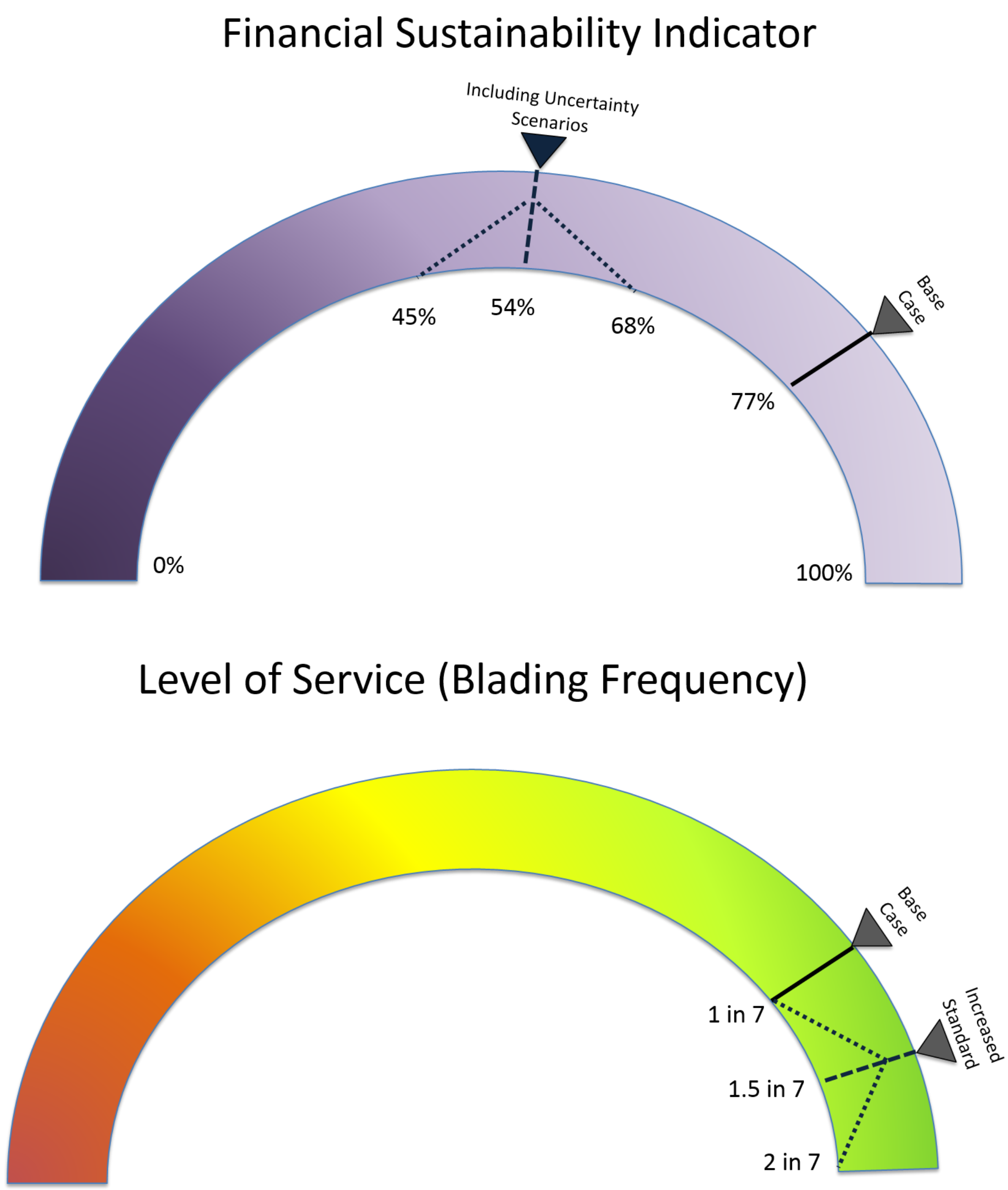

Figure 6.12: Levels of Service for Hypothetical Network Base Case and Uncertainty Scenarios

[31] This does not include the potential that there would be indirect impacts due to a change in standards to increase affordability, or due to extreme rainfall event as it was assumed that in the event of the rainfall event the network would require reconstruction.

The network financial sustainability indicator level of service was impacted by the occurrence of the events in a negative way. As with the hypothetical example there is risk in the outcome of the network AW which would directly impact the level of service. Therefore the risk is included in the level of service diagram through the use of a triangular distribution[32]. This allows both the expected value for the level of service (network financial sustainability indicator) to be illustrated, as well as the associated risk. If the events occur then the network financial sustainability indicator would have an expected value of 54%[33] (shown on the level of service with a straight dashed line), with potential outcomes ranging from 45-68% (shown with the triangular distribution dashed lines).

The second level of service used for this hypothetical example was the frequency of the blading of the roads. This level of service was only sensitive to the event of changing standards due to increased usage. Figure 6.12 shows that with the occurrence of the event of changing standards then the frequency of blading would increase from 1 time every seven days to an expected 1.5 times every seven days. As with the network financial sustainability indicator, there was uncertainty in the outcome of this level of service. This uncertainty is represented through the triangular distribution shown with dashed lines. This indicates that the level of service could vary from blading 1 time every week to 2 times every week.

6.7 Summary

This chapter has illustrated how the LCC model that was developed could be applied to a hypothetical rural road network. The model was verified against an existing tool to ensure that the deterministic portion of the model was correct. There were a number of decisions and events that included uncertainty that were considered within this example (i.e. new technology, changing standards, increasing material costs, and extreme weather events). These events were first considered individually, but then were used to estimate the event outcomes (network AW) given the potential outcomes of the events and the associated probabilities.

[32] A triangular distribution was shown for illustrative purposes only, the type of distribution would be dependent on the event.

[33] Network Financial Sustainability Indicator = Network Annual Budget / Network AW * 100% = $370,000 / $678,900 * 100% = 54%

The hypothetical network illustrated that given the occurrence of the defined events the expected network AW was expected to increase from $481,400 per year (with no events occurring) to $678,900 per year. The expected network AW was $195,700 per year more when the events occurred. This resulted in an increase of 41% in the anticipated network AW.

The levels of service that were used for this case study were the network financial sustainability indicator and the frequency of blading of the gravel roads. It was determined that the first level of service (the network financial sustainability indicator) was sensitive to the occurrence of the events. If the events occur, then the network sustainability indicator would be expected to decrease from 77% (if the events do not occur) to 54% if the uncertainty events are included. There was risk in the outcome of the network financial sustainability indicator which could potentially vary from 45-68%. The frequency of the blading of the gravel road level of service was only sensitive to the event of changing standards. Given the event of changing standards (due to increased usage) the frequency of blading was expected to increase from 1 time per week (with no changing standards) to 2 times per week. There was risk in this level of service as well with the frequency of blading potentially ranging from 1 time per week to 2 times per week.

This hypothetical example illustrated that the event outcomes (network AW) and levels of service were sensitive to the occurrence of the events (i.e. new technology, changing standards, increasing material costs, and extreme weather events). The information provided by quantifying the event outcomes, in terms of network AW and levels of service, supports informed decision making. For infrastructure managers operating under network variable uncertainty, ignoring this uncertainty may significantly underestimate the funds required for providing services in the long term, impacting the overall financial sustainability of these services.

CHAPTER 7 CASE STUDY 1 – TOWN OF SHELLBROOK

7.1 Introduction

The Town of Shellbrook is a small urban center located between Saskatoon and Prince Albert in the province of Saskatchewan. The population of the Town is 1,433 (Government of Canada, 2014). The Town acts as both a regional hub to the surrounding rural area, as well as a bedroom community to the City of Prince Albert. A large quantity of the Town infrastructure was originally constructed in the 1960's and a significant amount of this original infrastructure is still currently in use. This case study focused on the sanitary sewer main network that exists throughout the Town. The purpose of the sanitary sewer network is to support the safe and efficient removal of sanitary waste with minimal impact on the environment. The sanitary sewer network in the Town of Shellbrook consists of 19,235 m of sanitary mains (composed of PVC, concrete, clay, High-density Polyethylene, and relined concrete), three lift stations, one pumping station, a waste water treatment plant, and a three-cell lagoon. This case study looked only at the sanitary mains. A map illustrating the extent of the Town sanitary sewer mains, as well as the associated years of construction of the mains, is illustrated in Figure 7.1.

The sanitary mains that are shown in green are those that were constructed in the 1960's during the original installation of Town infrastructure. These 1960 lines make up 33% of the sanitary main network. The Town of Shellbrook is concerned about the aging sanitary sewer main network as most of the mains are expected to last approximately 60 years, meaning that many of the sanitary mains are expected to require renewal in the near term. The older sanitary mains are predominantly concrete, and preliminary analysis has determined that approximately 70% of the mains are expected to be good candidates for trenchless technology. The use of trenchless technology is a new technology for the Town of Shellbrook, and there is uncertainty if the technology would be a good economic alternative for renewing the Towns sanitary sewer mains. To look at the potential outcomes associated with the decision to implement the new technology, it was necessary to define the base case network AW given current activities. A summary of the costs associated with renewing the Shellbrook sanitary network are outlined in Table 7.1. For a detailed breakdown of the sanitary network refer to Appendix C.

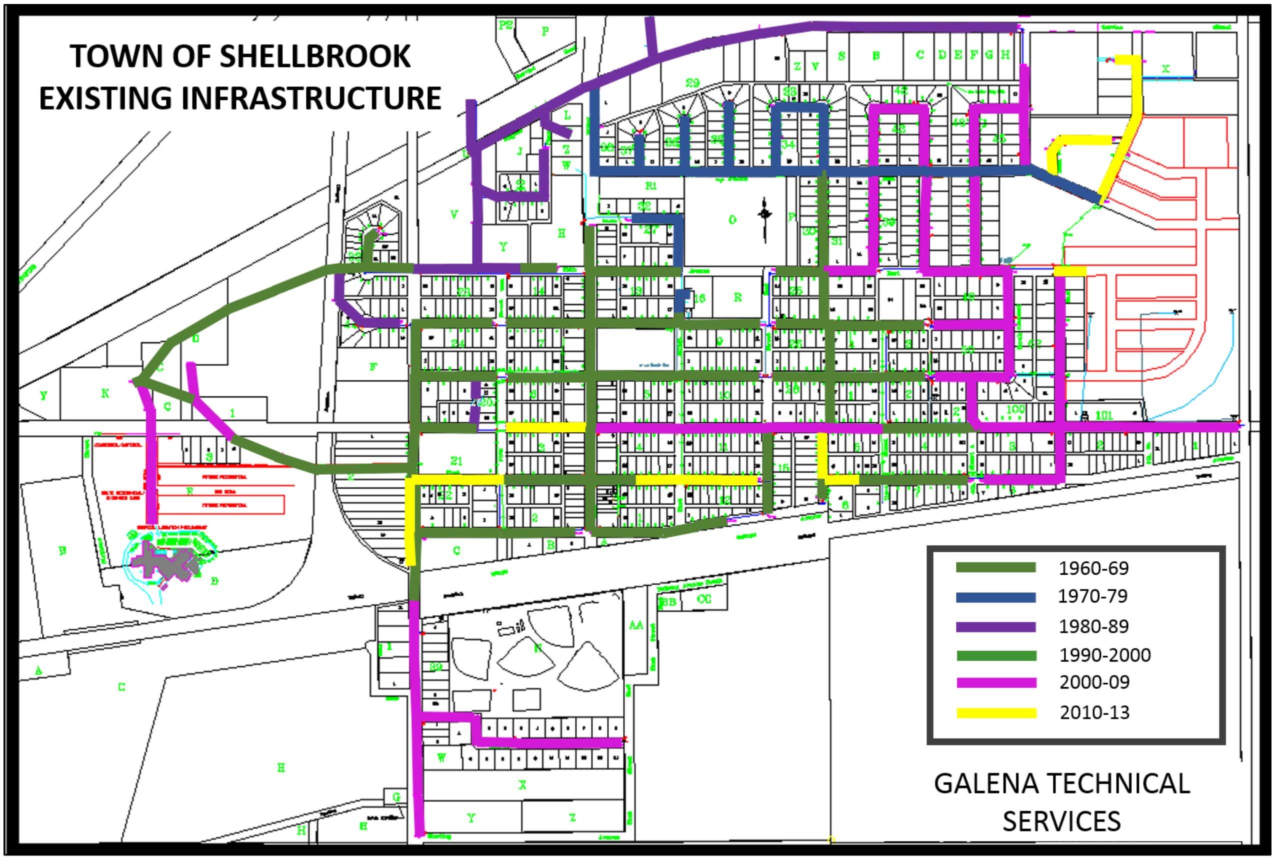

Figure 7.1: Town of Shellbrook Sanitary Sewer Line Network

Table 7.1 indicates, in the first column, the various types of sanitary mains that comprise the Shellbrook sanitary main network. These range by both pipe diameter and pipe type. The total length of each type of pipe is indicated by total meters within the network. The conventional replacement cost is also indicated based on information provided by Town staff. The expected lives for each of the pipe types is also included in the table. The last row in Table 7.1 shows the total length of the sanitary main network, along with the total annual operating and maintenance costs.

Table 7.1: Shellbrook Sanitary Network Base Case Details

	Length (m)	Conventional Replacement Cost (2014 $)[34]	Expected Life	Details
50mm PVC	155	$300 /m	70 years	
100mm PVC	189	$790 / m	70 years	
200mm PVC	10,603	$800 / m	70 years	
200mm Concrete / Clay	964	$800 / m	55 years	
250mm PVC	4,859	$820 / m	70 years	
250mm Concrete / Clay	2,112	$820 / m	55 years	
250 HDP	353	$820 / m	70 years	
Operations and Maintenance[35]	19,235	Total network O & M $54,000	Annually	Includes flushing of the mains and repairs to the mains.

7.2 Shellbrook Base Case Life Cycle Costs

The Town of Shellbrook sanitary network is an existing network at some point in its life cycle, not a proposed network as was illustrated for the hypothetical network. In developing the LCCs for this case study the existing network was defined. This is shown in Figure 7.2 which indicates upcoming expenditures, reflecting the current age and condition of the assets making up the network. The upcoming expenditures are illustrated for the next 20 year period. For more detailed LCC profiles of the existing sanitary network refer to Appendix C.

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[34] For the conventional replacement it was assumed that the sanitary mains would be replaced with a PVC material pipe with the same diameter as the original main.
[35] For a detailed breakdown of the operating and maintenance costs refer to Appendix C.

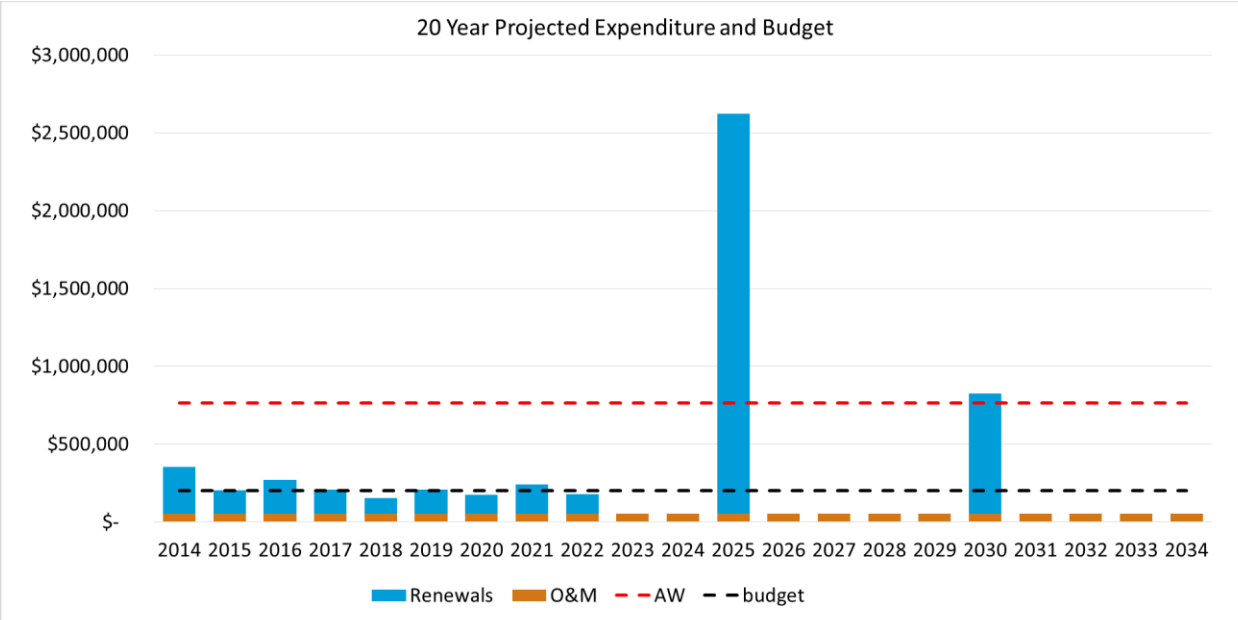

Figure 7.2: Shellbrook Sanitary Network Upcoming Expenditures[36]

As with the previous LCC profiles the bars illustrate the projected expenditures. The expenditures consist of operating and maintenance costs, renewals, and disposals. The red dotted line illustrates the network AW (expected over the long term) and the black dotted line the current budget. This LCC profile illustrates that for the next 5-10 year period of the asset life, the current budget of $200,000 per year is close to sufficient for the operating, maintenance, and renewals that are anticipated. However, around the year 2025 a significant amount of renewal is expected to be required. It is unlikely that all of the renewals would be carried out in one or two years, but the pipes cannot be expected to last forever, and based on their expected lives the renewals are anticipated in the years shortly before or after 2025. It would be critical that the organization had some strategy for how these peaks of renewal would be dealt with.

When looking at the long term financial sustainability of the infrastructure network it can be helpful to look at the expected ongoing, average life cycle costs[37]. The LCC profile developed

[36] All costs are shown in current day dollars.
[37] These would be the LCCs calculated as if the network were a proposed network, and used to estimate long term ongoing annual costs.

for estimating the average long term LCCs is illustrated in Appendix C. The calculated AW and PW for the Shellbrook sanitary mains is illustrated in Table 7.2.

Table 7.2: Calculation of AW and PW for Base Case Shellbrook Sanitary Network.

	Hypothetical Base Case Model Results
***AW*[38]**	$716,900
PW	$17,923,100

The network average long term AW for the Town of Shellbrook sanitary mains was calculated as $716,900 per year. The current budget of $200,000 per year for the sanitary network is 28% of the estimated network AW. This indicates that the network is financially unsustainable in the long term at current funding levels.

7.3 Defining Shellbrook Network Uncertainty Scenarios

As previously indicated the purpose of this case study was to look at the potential outcomes of the Town making the decision to implement new trenchless technology, and how this information might impact decision makers in managing this network. The opportunity for the Town to use trenchless technology would result from a voluntary implementation by the Town. This new (to Shellbrook) technology would be implemented in an attempt to minimize the costs associated with the renewal of aging sanitary main infrastructure. While it is expected that this trenchless technology would reduce the costs associated with sanitary main renewal, the expected useful life of the new lined mains would be less than that expected with a conventional replacement of the sanitary mains. It would support decision making if the outcome of this decision could be analyzed in terms of associated risks in terms of potential event outcomes.

The first step in looking at the network variable uncertainty for the Town of Shellbrook was to review the flow charts that were introduced in earlier chapters. The uncertainty flow chart

[38] A 4% discount rate was used for the calculation of AW and PW.

was utilized to determine which network variable uncertainty scenarios would be considered for the network, as illustrated in Figure 7.3.

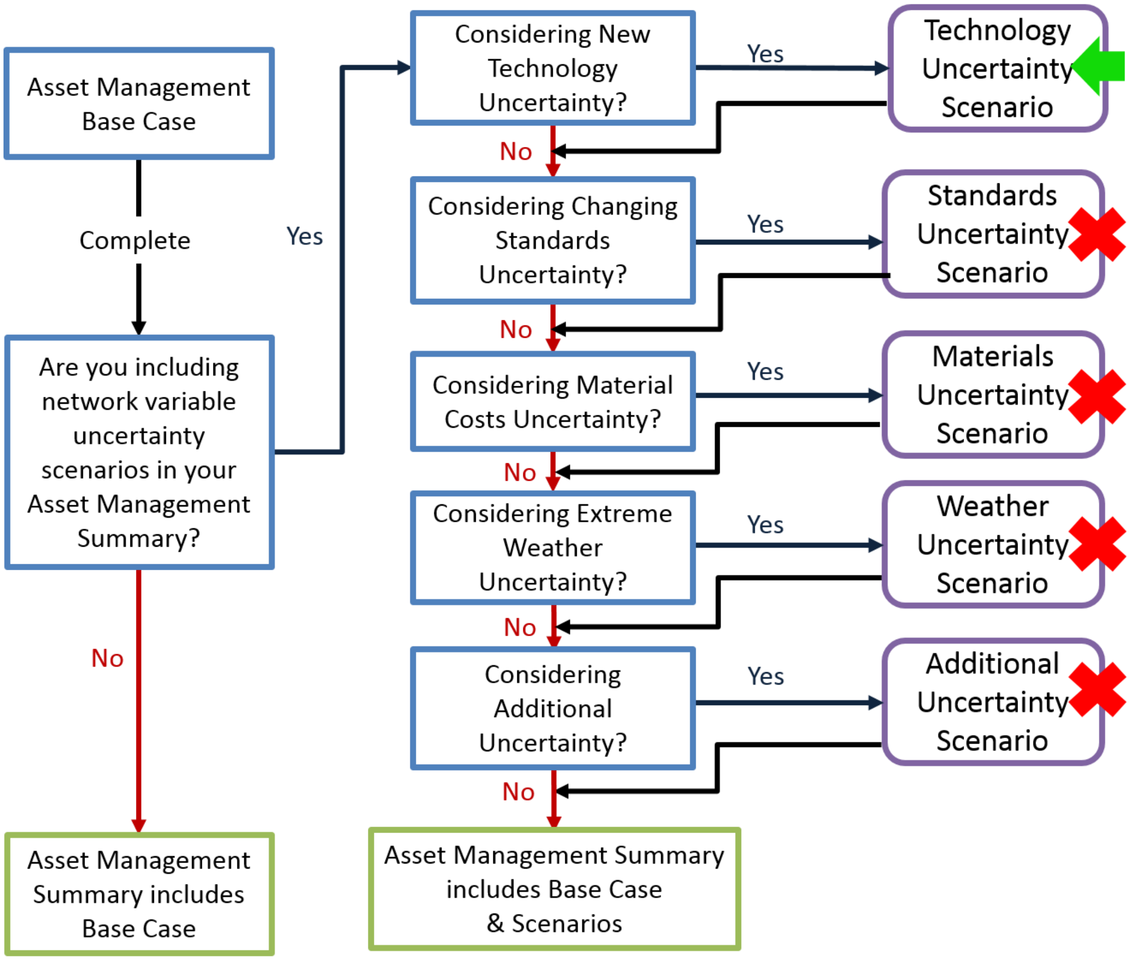

Figure 7.3: Shellbrook Sanitary Uncertainty Flow Chart

After review and consultation with Shellbrook staff it was determined that the analysis would review the decision to implement the new trenchless technology. For this case study this decision was the only event considered. With the uncertainty scenario defined it was necessary to review how the decision to implement the new technology would impact the event outcomes, namely the network AW and levels of service. The impacts of the uncertainty scenarios were defined through the use of the flowchart shown in Figure 7.4.

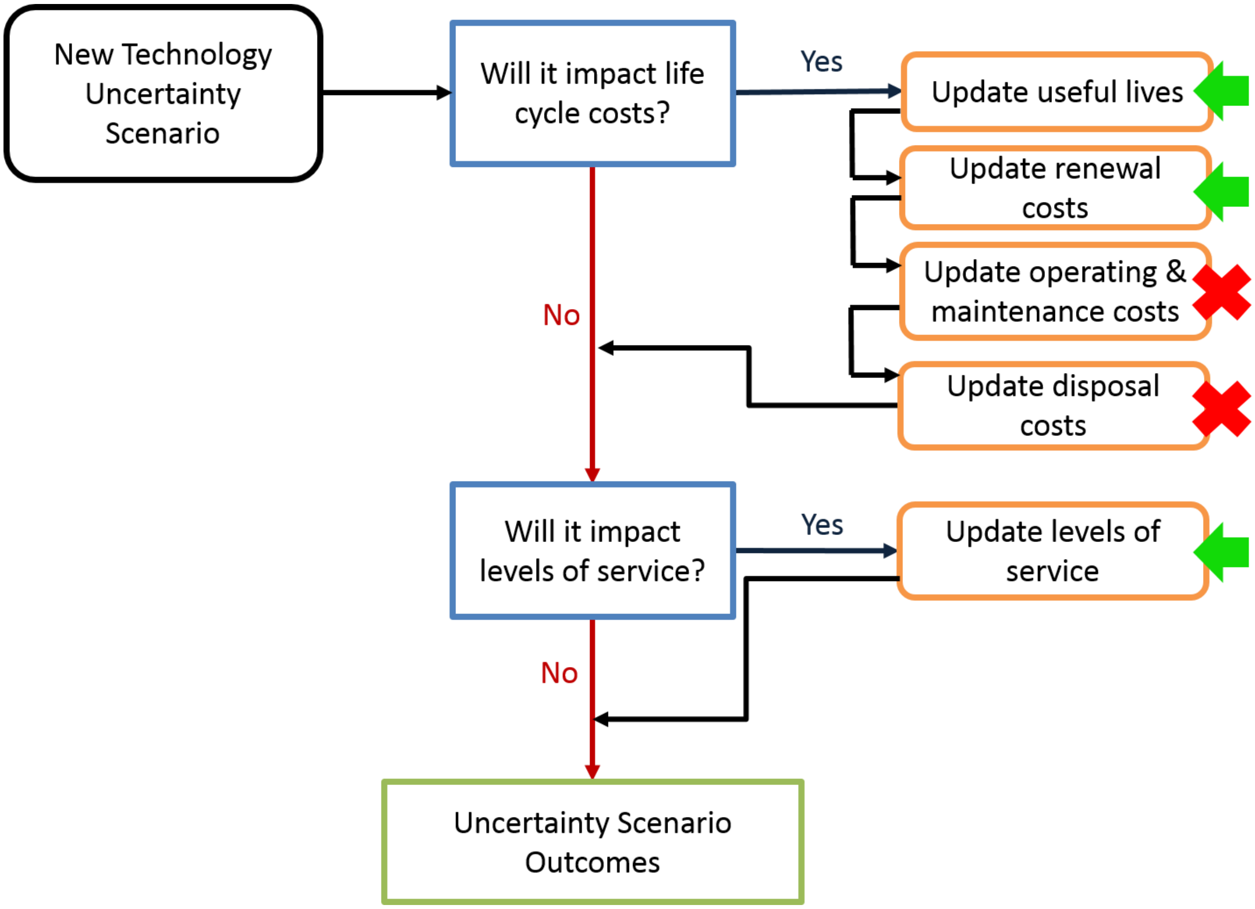

Figure 7.4: Flowchart of New Technology Scenario for Shellbrook Sanitary Network

After review of the new technology uncertainty scenario it was determined that the uncertainty would impact the LCCs in a number of ways requiring updates of the: (1) useful lives, (2) renewal costs, and (3) levels of service, (indicated with green arrows in Figure 7.4). The operating and maintenance costs and disposal costs would not be impacted by the uncertainty (indicated with red 'X' in Figure 7.4). Once the aspects of the uncertainty scenarios had been defined, and through consultation with Town staff, the impacts to the LCCs were quantified and are illustrated in Table 7.3.

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Table 7.3: Shellbrook Sanitary Network New Technology Details

	Length (m)	Conventional Replacement Cost[39] (2014 $)	Expected Life (conv.)	Relining Cost	Expected Life (reline)	Details
50mm PVC	155	$300 /m	70 years	--	--	
100mm PVC	189	$790 / m	70 years	--	--	
200mm PVC	10,603	$800 / m	70 years	$510 / m	50 years	0-100% relined
200mm Concrete / Clay	964	$800 / m	55 years	$510 / m	50 years	0-100% relined
250mm PVC	4,859	$820 / m	70 years	$550 / m	50 years	0-100% relined
250mm Concrete / Clay	2,112	$820 / m	55 years	$550 / m	50 years	0-100% relined
250 HDP	353	$820 / m	70 years	--	--	
Operations and Maintenance[40]	19,235	$54,000	Annually			Includes flushing of the mains and repairs to the mains.

Table 7.3 compares the values used in the calculation of the base case LCCs to those used for the LCC's given the decision to implement the new technology. The uncertainty in this decision results from the variability in what portion of the sanitary network can implement the new technology and not in the actual values associated with the costs or useful lives of the new technology. The first column in Table 7.3 indicates the length of each type of pipe present in the

[39] These conventional replacement costs include the cost of rehabilitation of the road structure and surface overlying the sanitary main.
[40] The operating and maintenance costs are broken down into further detail in Appendix C.

network. Each pipe type has an associated replacement cost and expected life given a conventional replacement treatment. The new technology, relining of the mains, would only be possible for the 200 – 250 mm diameter PVC, concrete, or clay pipes. For these potential new technology candidates, the cost of the trenchless technology and the expected life with the new technology treatment is indicated.

7.4 Shellbrook Uncertainty Scenarios Life Cycle Costs

With the new technology uncertainty scenario LCCs defined, the model was integrated with the DPL tool. As shown previously, this requires the development of an influence model in DPL. The decision for this model was the implementation of new technology, while the uncertainty exists in the amount of the network suitable for relining. The output of the DPL model was the network AW. The model that was developed in DPL and linked to the LCC model is illustrated in Figure 7.5.

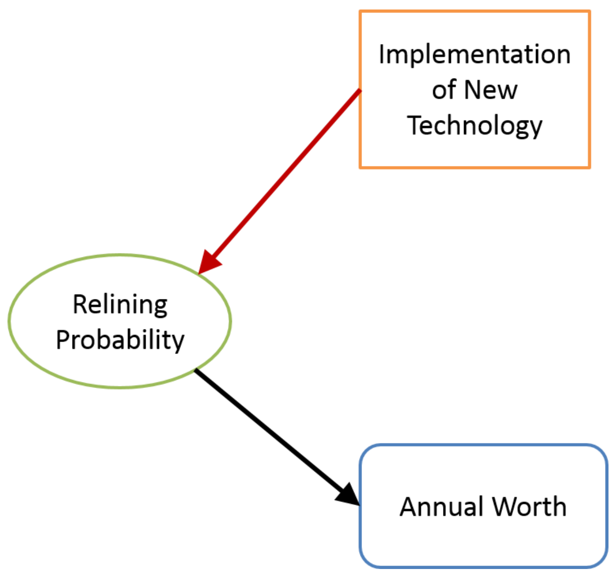

Figure 7.5: Shellbrook Sanitary Uncertainty DPL Influence Model

The DPL influence model includes a decision node (shown in the orange square) which dictates if the new technology is implemented or not. The uncertain variable exists in the relining probability (green oval) node which represents the percentage of the network suitable for relining. The uncertain variable includes a low, nominal, and high value for the percent of the network suitable for relining, along with an associated probability for each[41]. The model output is the network AW. This model uses the defined values for the relining probability (in DPL) and utilizes excel as a calculator and then gathers and summarizes the results. The first probabilistic output from the DPL tool that was reviewed was the tornado diagram.

7.4.1 Shellbrook Sanitary Network with Uncertainty Tornado Diagram

The tornado diagram is most useful when there are a number of variables that include uncertainty. For this scenario, the only uncertainty existed in the percentage of pipe relining. As such the tornado diagram illustrates the upper and lower values given the uncertainty in the variable. The tornado plot is shown in Figure 7.6.

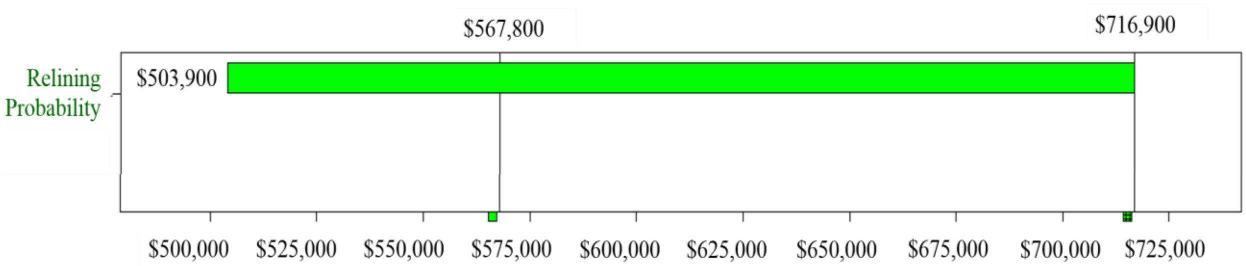

Figure 7.6: DPL Tornado Plot for Significance of Shellbrook Uncertainty Variables

In the tornado diagram, the expected network AW (relining set at 70% suitable lines) is indicated at $567,800 per year. The green bar represents the lower and upper outcomes given the uncertainty within the percentage of the network suitable for relining. The second line indicated on the tornado diagram shows a network AW of $716,900 per year, which represents the expected network AW if the decision is to not implement the new technology (base case). The tornado diagram provides a summary of how sensitive the model output is based on the uncertainty within the relining probability variable. The AW ranges from $503,900 per year if 100% of the mains are suitable for relining to $716,900 per year if 0% of the mains are suitable for relining which is a variability of $213,000 per year.

[41] The ‘low’ value = 0% of the network suitable for relining and has an associated probability of 30%. The ‘nominal’ value = 70% of the network suitable for relining and has an associated probability of 40%. The ‘high’ value = 100% of the network suitable for relining and has an associated probability of 30%.

7.4.2 Shellbrook Sanitary Network with Uncertainty Risk Curve

The Shellbrook sanitary network AW risk curve is shown in Figure 7.7. The risk curve shows the potential event outcomes (network AW) with associated cumulative probability. The vertical axis indicates the cumulative probability for any given value along the risk curve. The expected value, for the decision to implement the new technology, is indicated by the vertical line shown with the AW value of $593,400 per year (red = yes implement new technology). The risk curve also indicates the expected value if the new technology is not implemented (green = no do not implement new technology). The base case network AW is shown as a vertical line (indicating there is no risk) with an expected network AW value of $716,900 per year. If the new technology is implemented the risk associated with the potential event outcomes ranges from a network AW of $503,900 to $716,900 per year.

In Figure 7.7 the risk curve illustrates that if the organization implements the new technology, then the expected network AW is $123,500[42] per year less than if they do not implement the new technology. By making the decision to implement the new technology the Town of Shellbrook would expect to reduce the network AW by 17%.

[42] AW (Base Case) – AW (New Technology) = $716,900 - $593,400 = $123,500.

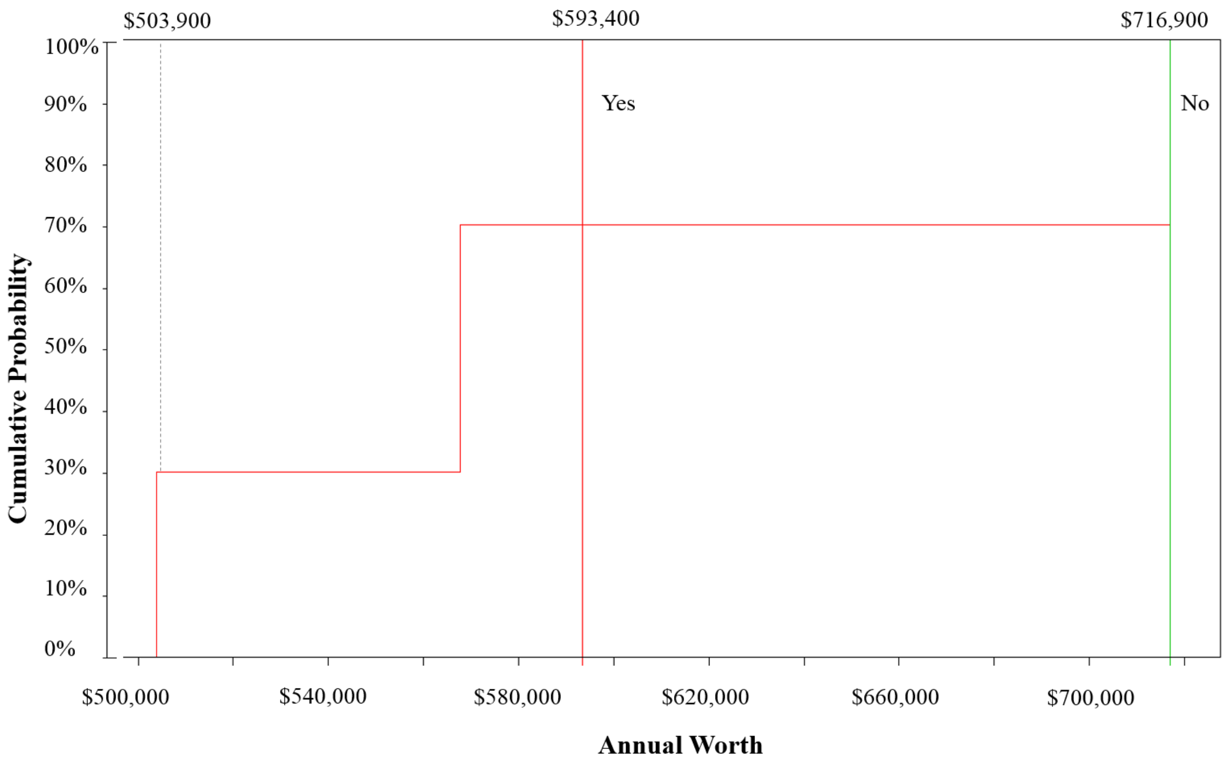

Figure 7.7: DPL Risk Curve for Shellbrook Sanitary Network AW Including Uncertainty

7.5 Levels of Service

With the network AW defined for the decision of implementing or not implementing the new technology, the next piece of information required to support informed decision making was the impact to the levels of service. As with the hypothetical example the first level of service that was considered was the network financial sustainability indicator (Annual Budget/AW). For this case study, through discussions with staff, it was determined that the second level of service that would be considered would be the ability of the organization to meet standards set by governing bodies (Government of Saskatchewan, 2002). The base case levels of service are illustrated in Figure 7.8.

The base case levels of service provide a comparison point for the impact of the decision on the levels of service. The network financial sustainability indicator for the base case was calculated as 28%[43]. The second measured level of service was the meeting of legislative requirements, which would include both provincial and federal regulations. Meeting of current legislations is a pass or fail level of service, meaning the organization either does or does not meet the set requirements. It was determined, through consultation, that the Town currently meets all required standards.

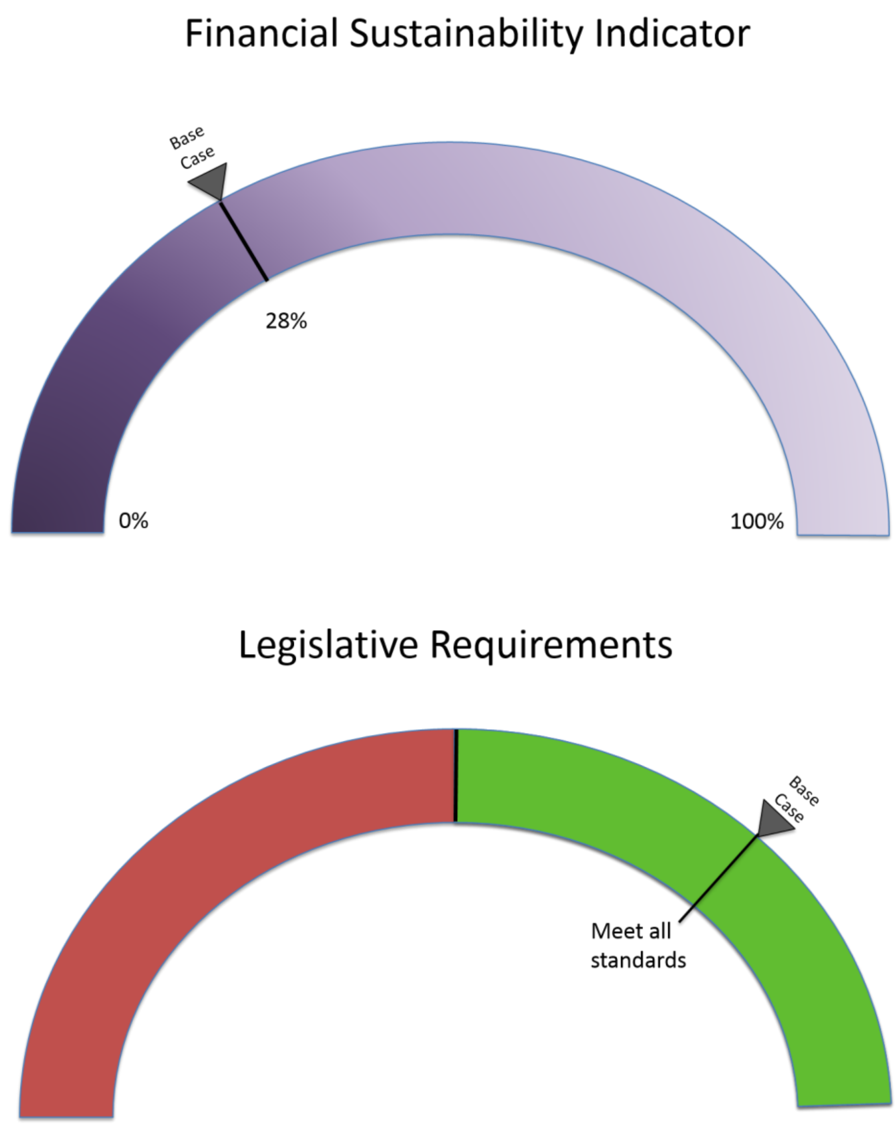

Figure 7.8: Levels of Service for Shellbrook Sanitary Network Base Case

[43] Sustainability Indicator = Annual budget / Network AW * 100% = $200,000 / $716,900 * 100% = 28%

With the base case levels of service defined it was possible to compare the impact of the decision to implement the new technology against the base case levels of service. It is critical that discussions regarding the potential event outcomes of a decision or event also include a discussion on the potential impacts to the levels of service. The revised levels of service are illustrated in Figure 7.9.

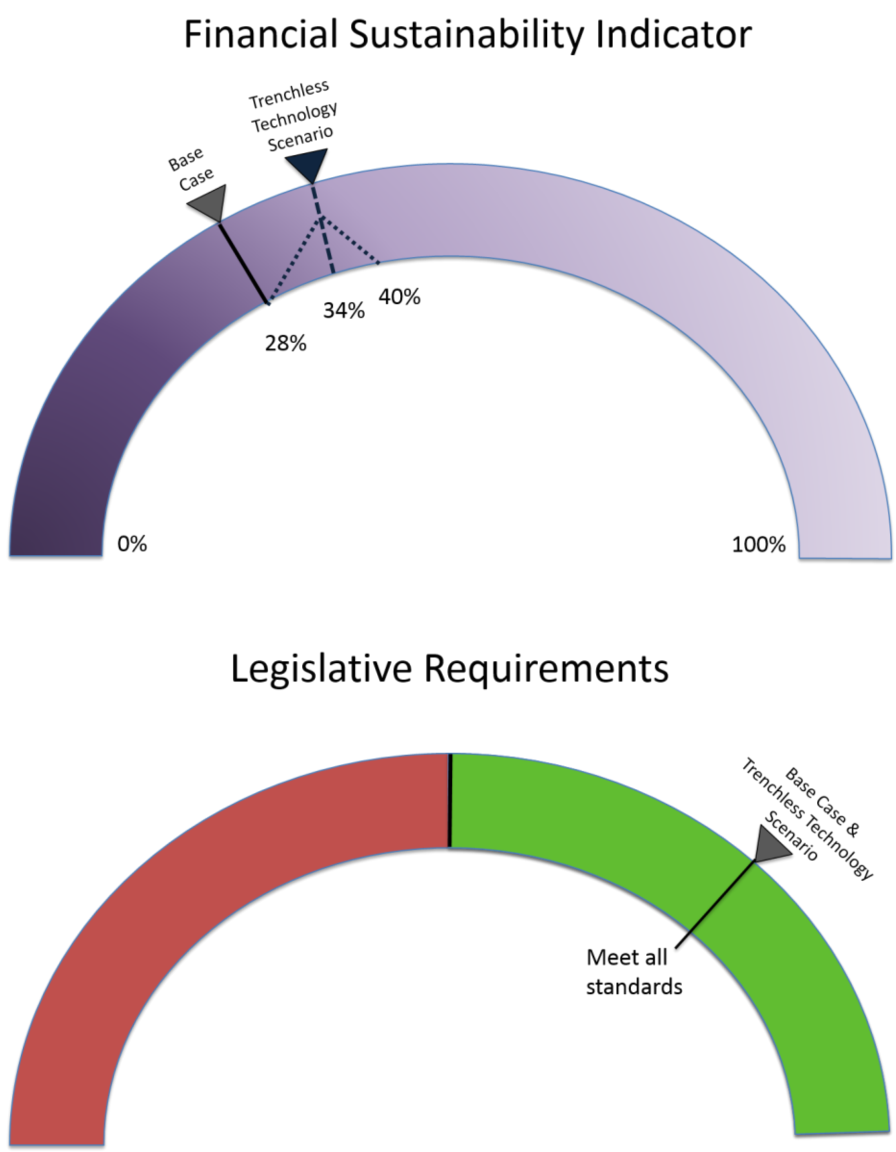

Figure 7.9: Levels of Service for Shellbrook Sanitary Network New Technology Scenario

The network financial sustainability indicator level of service was impacted by the decision to implement the new technology in a positive way. As with the hypothetical example there is risk in the potential network AW which would directly impact the level of service. Therefore the risk is included in the level of service diagram through the use of a triangular distribution[44]. This allows both the expected value for the level of service (network financial sustainability indicator) to be illustrated, as well as the associated risk. If the decision is made to implement the new technology the network financial sustainability indicator would have an expected value of 34%[45] (shown on the level of service with a straight dashed line), with potential outcomes ranging from 28-40% (shown with the triangular distribution dashed lines). The second level of service indicator that was used for this case study, was a measure of the meeting of standards and regulations. The base case for the Town sanitary network was a meeting of all regulations, this was not expected to be impacted by the decision to implement new technology, and as such would not be impacted by the decision.

7.6 Summary

This case study looked at the implications of deciding to implement new trenchless technology for the renewal of the Town of Shellbrook sanitary main network. The Town has a large quantity of aging mains (33% of the network) constructed in the 1960's which are expected to require renewal in the near term. There is uncertainty in implementing the new technology and informed decision making would be supported by better understanding the potential event outcomes from deciding to implement the new technology. The implications of the decision were represented by potential impacts to the network AW and levels of service.

This case study demonstrated how the model developed and utilized for the hypothetical network in previous chapters could be applied to a real life scenario to support informed decision making. The first aspect of the case study was to define the network AW for the base case. Through consultation with staff, the base case network AW was calculated as $716,900 per year[46]. This case study differed from the hypothetical example as the model was applied to an existing, as opposed to a proposed, network.

[44] A triangular distribution was shown for illustrative purposes only, the type of distribution would be dependent on the event.

[45] Network Financial Sustainability Indicator = Network Annual Budget / Network AW * 100% = $200,000 / $593,400 * 100% = 34%

[46] For the AW calculation a discount rate of 4% and a study period of 120 years was used.

Once the base case network AW and levels of service were defined, the decision to implement the new technology was analyzed. It was known that if the new technology was implemented that the sanitary main renewal costs would be reduced, however, there was uncertainty in the decision as it was unknown what percentage of the sanitary network would be suitable for relining. The sanitary mains suitable for relining could vary between 0-100%, but it was expected that 70% would be suitable. The event outcomes of the decision were calculated and illustrated that if the decision was made to implement the new technology than the expected network AW would be $593,400 per year. However, there was risk that the network AW could range from $503,900 to $716,900 per year. The expected network AW with the implementation of the new technology was $123,500 per year less than if the new technology was not implemented. This would result in a 17% reduction in the network AW.

The levels of service that were used for this case study were the network financial sustainability indicator and the meeting of requirements set by regulating bodies. It was determined that the first level of service (the network financial sustainability indicator) was sensitive to the decision, however, the second level of service (the meeting of regulations) was not. If the new technology was implemented the network sustainability indicator would be expected to increase from 28% (if the new technology was not implemented) to 34%. There was risk in the outcome of the network financial sustainability indicator which could potentially vary from 28-40%.

For decision makers this case study illustrates how the implications of making the decision to implement the new technology in terms of network AW and levels of service could be calculated in a credible and transparent way that can be effectively communicated. Having information regarding the potential impacts of network variable uncertainty on the network AW, and levels of service, allows decision makers to make fully informed decisions in the face of uncertainty.

CHAPTER 8 CASE STUDY 2 – RM OF WILTON

8.1 Introduction

The rural municipality (RM) of Wilton is located in the North West region of Saskatchewan. This region has seen significant growth due to the development of the heavy oil industry. Recent changes in the RM have seen the development of the Wilton Energy Park. While there are various industries present in the park one of the more significant ones is the Altex transload facility. This is a rail facility that has recently been expanded to have the capacity to load 100 rail cars per day. This number of rail cars of oil is the equivalent of 680-720[47] barrels of crude oil per railcar for a total of 68,000 – 72,000 barrels of oil being exported per day. Much of the oil being shipped out of the Altex facility is brought to the facility by truck. These industry developments have resulted in a significant increase in heavy truck traffic. The RM over recent years has seen an increase in both the volume and the weight of vehicles. There is uncertainty in managing a transportation network with such a rapidly increasing usage by increasingly heavier vehicles. A map illustrating the RM of Wilton road network is included in Figure 8.1.

The Wilton rural road network is comprised of 7 classes of roads, these allow for a variety of vehicle weights. Figure 8.1 indicates the road network by the thick black and colored lines, as well as the thinner black lines. The brown line indicates a provincial highway which is not maintained by the RM.

[47] According to the BNSF Railway Company (BNSF Railway Company, 2014)

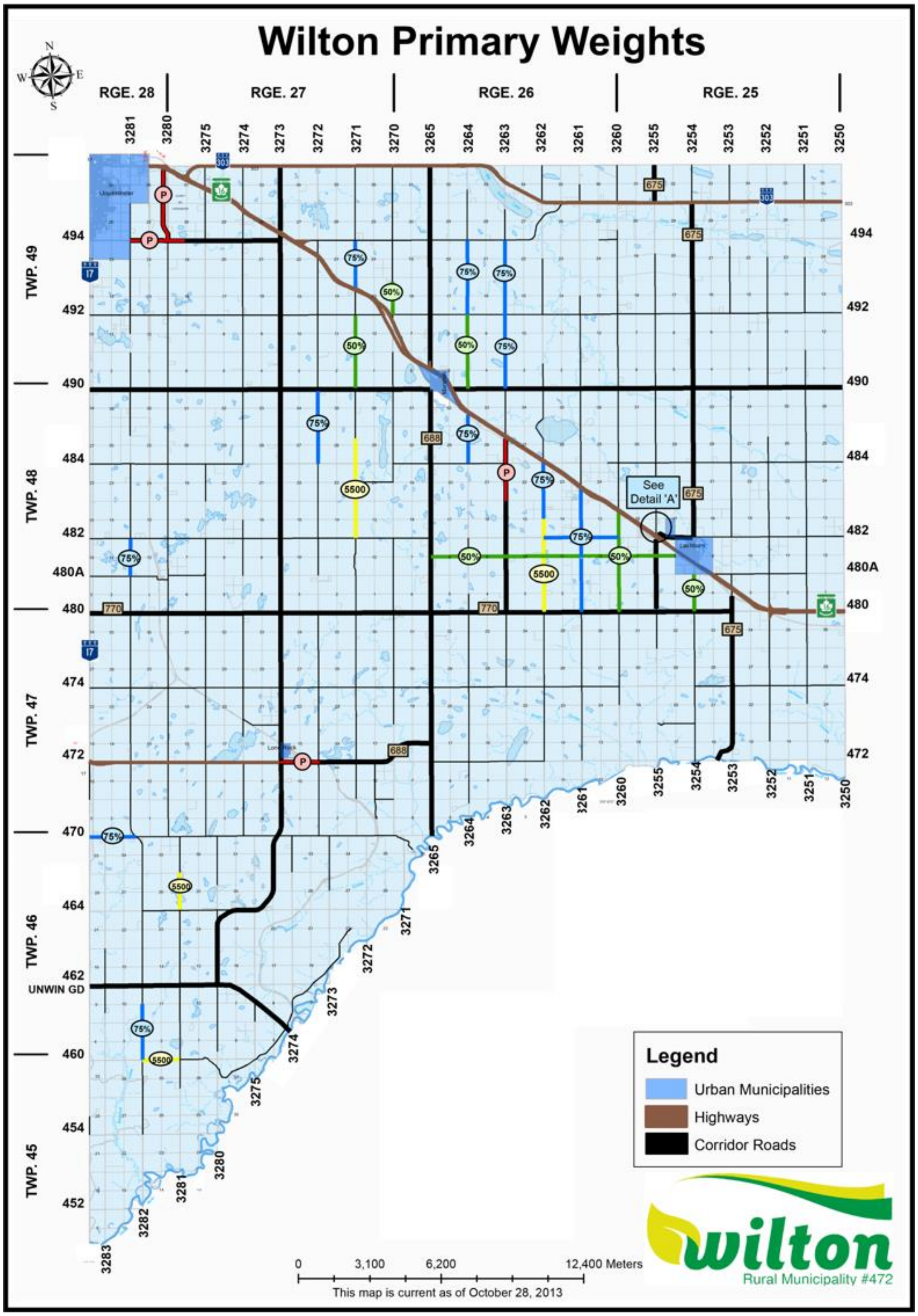

Figure 8.1: RM of Wilton Rural Road Network

8.2 Wilton Base Case Life Cycle Costs

The network that was considered for this case study was the RM of Wilton gravel road network. The RM of Wilton has 7 classes of roads. Class 1-3 are surfaced roads, Class 4-6 are gravel roads, and Class 7 are dirt roads. This case study only considered Class 4-6 roads, the gravel road network. These three classes of gravel roads are distinguished between each other mainly by the vertical and horizontal design of the road. Class 4 roads have a 10 m wide road top and a 1 m ditch, Class 5 roads have a 9 m wide road top and a 1 m ditch, while Class 3 roads have a 7 m top and a 0.5 m ditch. A summary of the road LCCs determined through consultation with the municipality are outlined in Table 8.1, for a detailed listing of the assets refer to Appendix D.

The purpose of this case study was to consider the impact of uncertainty within network variables on projected infrastructure financial requirements. This model was based on current properties of the RM gravel network and does not consider the technical elements of the performance of a gravel road network (e.g. traffic volume, traffic type, aggregate type, soil conditions).

Table 8.1: Wilton Gravel Road Network Base Case Details

	Length (km)	**Operating & Maintenance[48] ($/km)**	**Road Reconstruction (2014 $/km)**	**Timing**
Class 4	54	$11,900	$124,300	65 years
Class 5	327	$8,300	$124,300	65 years
Class 6	214	$5,900	$124,300	75 years

The LCCs outlined in Table 8.1 show each class of road on a separate row. The length of that road type within the network, along with the annual operating and maintenance costs[49], costs

[48] Operating and Maintenance costs include grading, regravelling, dust control and shoulder pulling as defined by the RM of Wilton.
[49] For a more detailed breakdown of operating and maintenance activities refer to Appendix D.

of road reconstruction and expected timing between reconstructions are also included. While the alignments of the various classes of roads are slightly different, for the purpose of this case study it was determined by RM staff that the reconstruction costs for each class of road was not significantly different. Generally speaking, the higher the class of road the higher the traffic volume, this is the reason that the Class 6 roads are expected to last longer than the Class 4 or Class 5 roads. Based on the network activity timing and costs defined through consultation, the LCC profile for the existing network was developed. The upcoming costs over the next 20 years for the Wilton existing gravel roads are illustrated in Figure 8.2. For a LCC profile of the full 70 year study period refer to Appendix D.

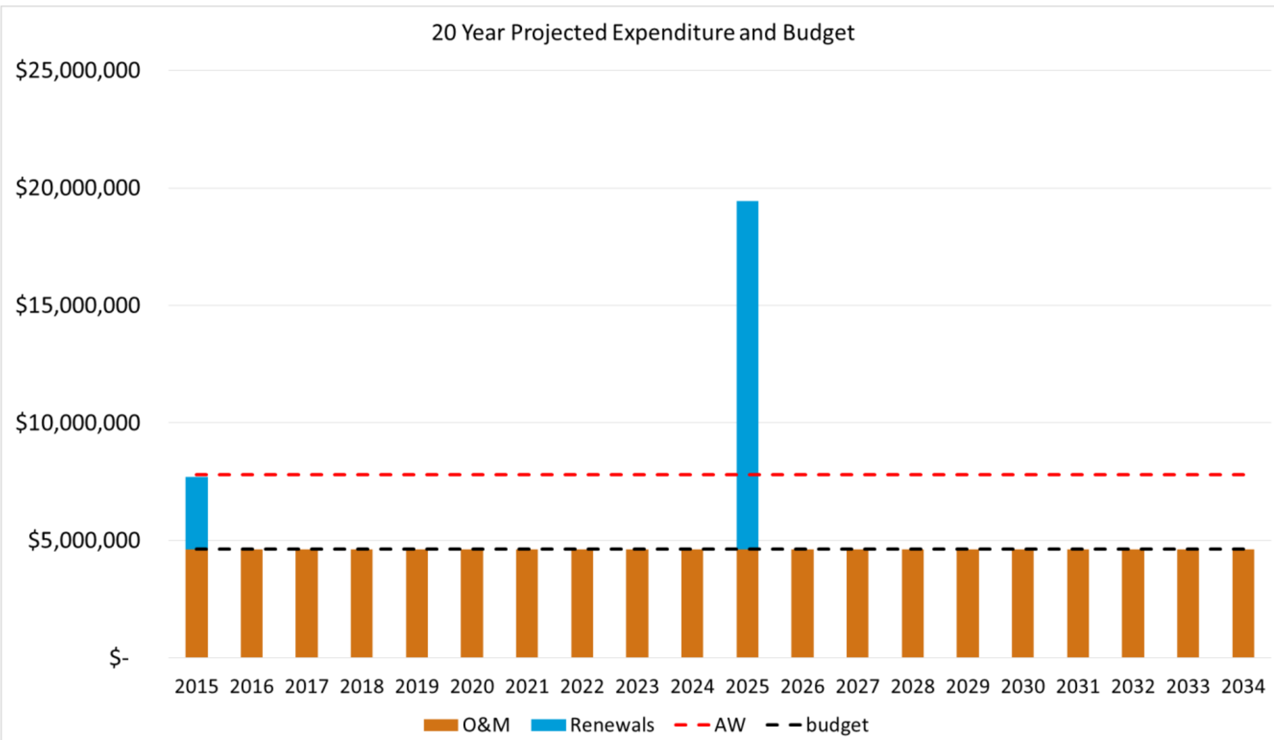

Figure 8.2: Wilton Gravel Road Network Upcoming Expenditures[50]

As with the previous LCC profiles the bars illustrate the projected expenditures. The expenditures consist of operating and maintenance costs, renewals, and disposals. The red dotted line illustrates the network AW (expected over the long term) and the black dotted line the current budget. The cash flow profile illustrates that the current budget of $4,621,300 for the RM of Wilton

[50] All costs are shown in current day dollars.

is sufficient to cover the operating and maintenance costs, however, the budget does not cover renewals of roads at the end of their useful lives. While the renewals are illustrated at the network level, and would be unlikely to occur in large spikes, there needs to be planning to ensure that the funds are available as required and that the network is sustainable going forward.

When looking at the long term financial sustainability of the infrastructure network it can be helpful to look at the expected ongoing, average life cycle costs[51]. The LCC profile developed for estimating the average long term LCCs is illustrated in Appendix D. The calculated AW and PW for the RM of Wilton gravel road network is illustrated in Table 8.2.

Table 8.2: Calculation of AW and PW for Base Case Wilton Gravel Road Network

	Hypothetical Base Case Model Results
AW[52]	$7,798,300
PW	$194,956,900

The average long term network AW for the RM of Wilton gravel road network was calculated as $7,798,300 per year. The current budget of $4,621,300 per year for the gravel road network is 59% of the estimated network AW. This indicates that the network is financially unsustainable in the long term at the current funding levels and at the current level of service.

8.3 Defining Wilton Uncertainty Scenarios

Having defined the base case network AW with the RM, it was necessary to review which events based on network variable uncertainty were of concern and would be considered within the analysis. One issue of particular concern for the RM was the increasing material costs associated with the purchase of gravel. The increases being experienced by the RM are not regular increases related to the general increases in all materials, but rather are disproportionate increases for the

[51] These would be the LCCs calculated as if the network were a proposed network, and used to estimate long term ongoing annual costs.
[52] A 4% discount rate and a 70 year study period was used for the calculation of AW and PW.

one type of material. These increases are related to the increasing scarcity in aggregate resources. Aggregate is an important material used for operating & maintenance, renewals, and new infrastructure. The scarcity in the availability of gravel has resulted in an increased purchase price of gravel material as well as increased haul distances, ultimately impacting the expected cost of gravel. A graph illustrating the changing cost of gravel in the RM of Wilton is illustrated in Figure 8.3.

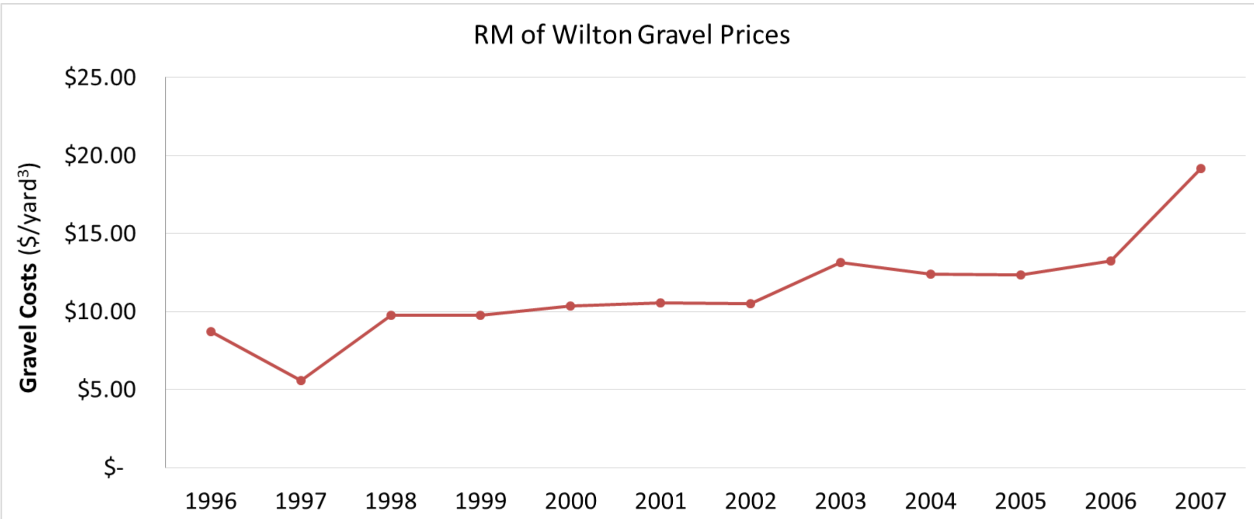

Figure 8.3: Historical Gravel Costs in the RM of Wilton[53]

Based on consultation and the historical increase in gravel costs it was determined that the average annual increase in gravel costs for the RM of Wilton would be approximately 7% above the expected increase in other material and labour costs. Since 1996 the increase in gravel costs has ranged from a decrease of 36% to an increase of 75% in any given year. The real average increase in gravel costs over the years of 1996 – 2007 was 11% per year. This was the most recent documented information available for the RM of Wilton gravel costs.

It was important for decision makers in the RM of Wilton to better understand the potential impact of the occurrence of the event of increasing gravel costs. A review of the impacts of network variable uncertainty was conducted by first looking at the network variable uncertainty flow chart

[53] This gravel cost information was collected across Saskatchewan over a number of years in preparation for the development of a gravel / truck loading model. The model was never completed or published. This information was provided by the Saskatchewan Association of Rural Municipalities.

for the RM of Wilton. The uncertainty flow chart was utilized to determine which network variable uncertainty scenarios would be considered for the network, this is illustrated in Figure 8.4.

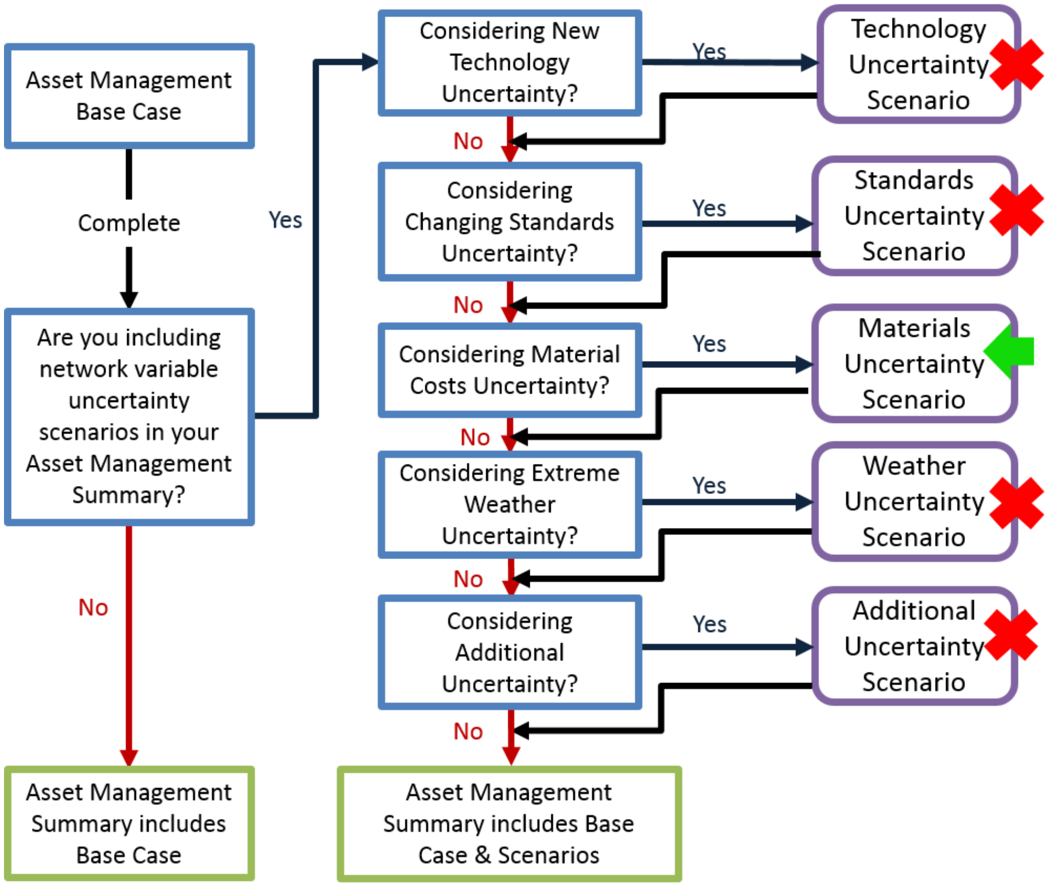

Figure 8.4: Wilton Transportation Uncertainty Flow Chart

Through consultation it was determined that this case study would include only the potential impacts due to the network variable uncertainty in the cost of gravel, as this was of the most concern. With the potential event of increasing gravel costs the impacts to the network AW and levels of service were reviewed. The impacts of the uncertainty scenario was defined through the use of the flowchart shown in Figure 8.5.

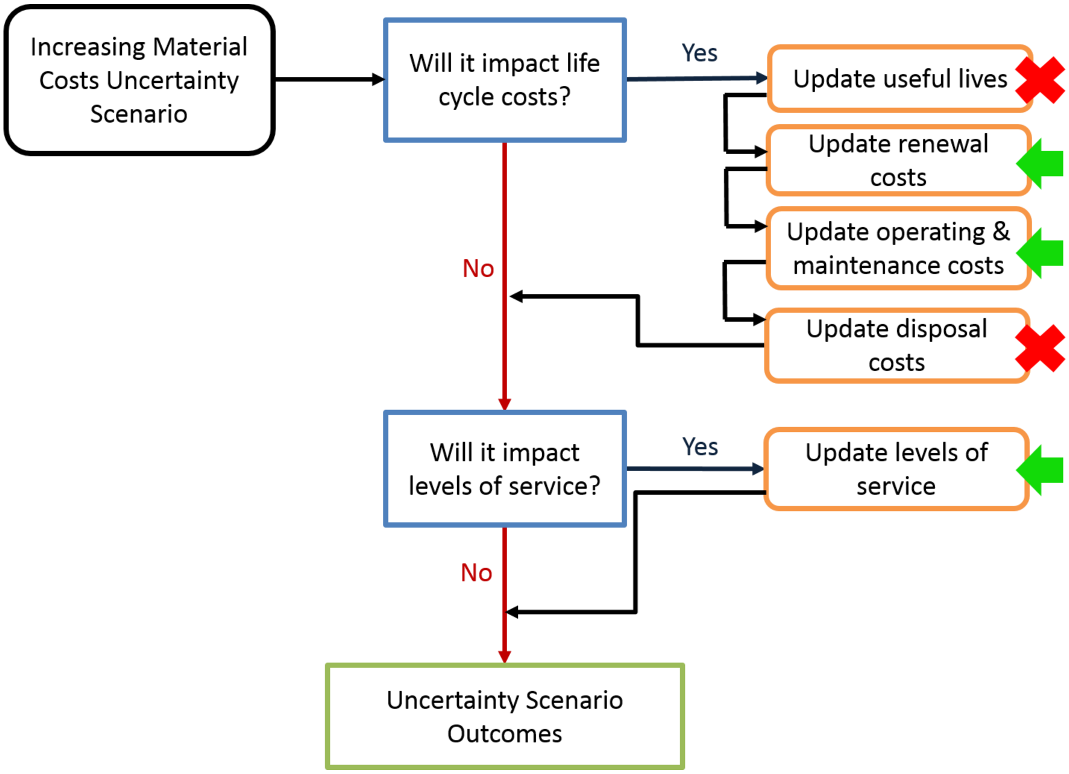

Figure 8.5: Flowchart of Increasing Material Costs Uncertainty Scenario for Wilton

After review of the impacts of the event of increasing gravel it was determined that the uncertainty would impact the LCCs in various ways including: (1) renewal costs, (2) operating and maintenance costs, and (3) levels of service, (indicated with green arrows in Figure 8.5). The useful lives and disposal costs would not be impacted by the uncertainty (indicated with red 'X' in Figure 8.5). With the potential impacts of the event defined, the revisions to the LCCs were quantified and are included in Table 8.3.

Table 8.3: Wilton Gravel Road Network Increasing Material Costs Details

	Operating & Maintenance ($/km)	**Road Reconstruction (2014 $)**	**Increasing Gravel Costs[54]**
Class 4	$11,900	$124,300	Gravel material costs increase by 2-10% per year to a maximum of 300%
Class 5	$8,300	$124,300	Gravel material costs increase by 2-10% per year to a maximum of 300%
Class 6	$5,900	$124,300	Gravel material costs increase by 2-10% per year to a maximum of 300%

Table 8.3 indicates how the LCCs were revised from the base case calculations to include the uncertainty in the increase of gravel costs. It was assumed that the material portion of the operating and maintenance[55] costs, and renewal costs would increase at a percentage rate each year, resulting in an exponential increase in the costs. It was roughly estimated that 11% of the operating and maintenance initial costs were due to the gravel material, while 30% of the reconstruction costs was due to the gravel material. The increase in material costs were estimated to increase annually by 7% per year, however, there was uncertainty that indicated that they may increase by as little as 2% per year or as much as 10% per year. The increase in gravel costs was capped at a maximum of 300%[56]. It was assumed that at this 300%[57] threshold other materials, new technologies, or other sources would be utilized. These increases in material costs are above that expected for other material and labour costs.

[54] For full details on the gravel index for the RM of Wilton refer to Appendix D.
[55] For further detail on the RM of Wilton operating and maintenance costs refer to Appendix D.
[56] The sensitivity of the upper gravel increase threshold was tested. If the threshold was set at 200%, and the expected uncertainty values were used as model inputs, the output AW would be 7% less than if the gravel costs were capped at 300%. If the threshold was set at 600%, again using expected uncertainty values, the output AW would be 13% more than if the increase was capped at 300%.
[57] In reality this threshold would be set based on the specific network and would likely require local and expert knowledge. The 300% cap was used for illustrative purposes only.

8.4 Wilton Uncertainty Scenarios Life Cycle Costs

With the increasing material costs scenario defined, the LCC model was revised to incorporate the potential event of increasing material costs. The model was then integrated with the DPL tool. This required an influence model to be developed within DPL. The potential event for this influence model was the increase in gravel material costs, while the uncertainty existed in the magnitude of the annual increase in costs. The output of the DPL model was the network AW. The model that was developed in DPL and linked to the LCC model is illustrated in Figure 8.6.

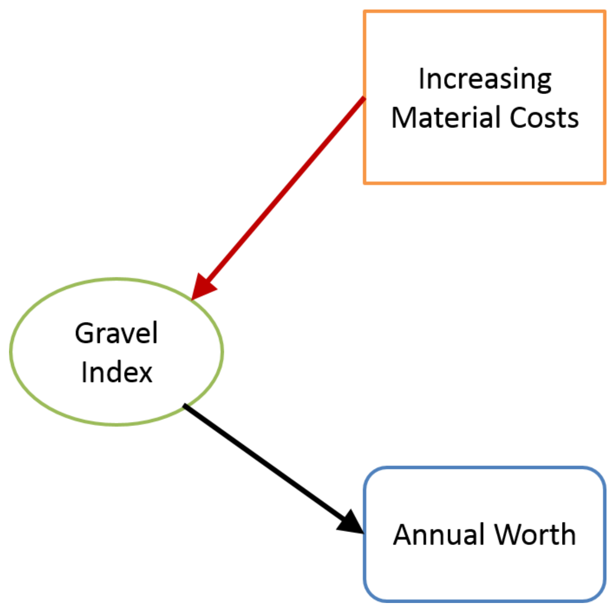

Figure 8.6: Influence Diagram for Wilton Uncertainty Scenario

The DPL influence model includes a decision mode (shown in the orange square) which dictates if the event of increasing material costs occurs or not. The uncertain variable exists in the gravel index (green oval) node which represents the rate of increase of the gravel material costs. The uncertain variable includes a low, nominal, and high value for the rate of the gravel cost increase, along with an associated probability for each[58]. The model output is the network AW.

[58] The 'low' value = 2% per year increase in gravel material costs with an associated probability of 30%. The 'nominal' value = 7% per year increase in gravel material costs with an associated probability of 40%. The 'high' value = 10% per year increase in gravel material costs with an associated probability of 30%.

This model uses the defined values for the rate of increase of gravel costs (in DPL) and utilizes excel as a calculator and then gathers and summarizes the results. The first probabilistic output from the DPL tool that was reviewed was the tornado diagram.

8.4.1 Wilton Rural Road Network with Uncertainty Tornado Diagram

The tornado diagram can be more useful when comparing a number of variables with uncertain values. However, for this case study there was only one uncertain variable, which was the annual increase in gravel costs. Due to the single variable with uncertainty, the tornado plot indicates the upper and lower bound outcomes given the uncertainty in the variable, this is illustrated in Figure 8.7.

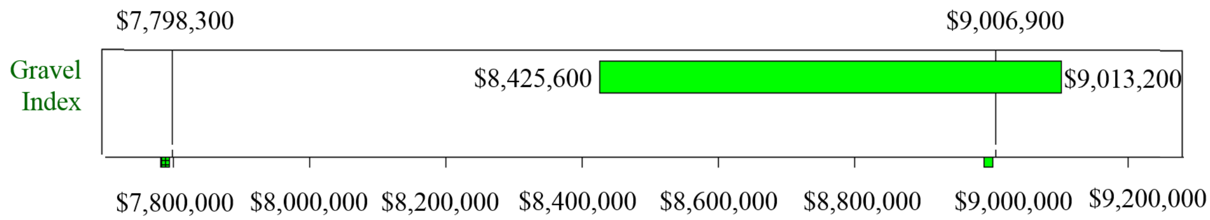

Figure 8.7: DPL Tornado Plot for Significance of Wilton Uncertainty Variables

In the tornado diagram, if the event of the gravel costs rising occurs, then the expected network AW is indicated at $9,006,900 per year. The green bar represents the lower and upper outcomes given the uncertainty within the gravel cost increase. The second line indicated on the tornado diagram indicates a network AW of $7,798,300 per year, which represents the expected network AW if the event of the increasing gravel costs does not occur. The tornado plot gives an indication of how sensitive the model output (network AW) is to the uncertainty in the gravel index variable. The AW ranges from a lower bound of $8,425,600 per year to $9,013,200 per year at the upper bound, this is a range of $587,600 per year depending on the rate of the gravel cost increase. The uncertainty risk curve was reviewed after the tornado plot.

8.4.2 Wilton Rural Road Network with Uncertainty Risk Curve

The RM of Wilton gravel road network AW risk curve is shown in Figure 8.8. The risk curve shows the potential event outcomes (network AW) with associated cumulative probability.

The vertical axis indicates the cumulative probability for any given value along the risk curve. The expected value, for the event of gravel costs increasing, is indicated by the vertical line shown with the AW value of $8,861,400 (red = Yes event occurs). The risk curve also indicates the expected value if the event does not occur (green = No event does not occur) at an expected network AW of $7,798,300 per year. If the event does not occur, there is no risk in the potential outcomes, and as such this curve is shown as a vertical line. If the event of the gravel costs increasing does occur the potential event outcomes range from a network AW of $8,425,600 to $9,103,200 per year.

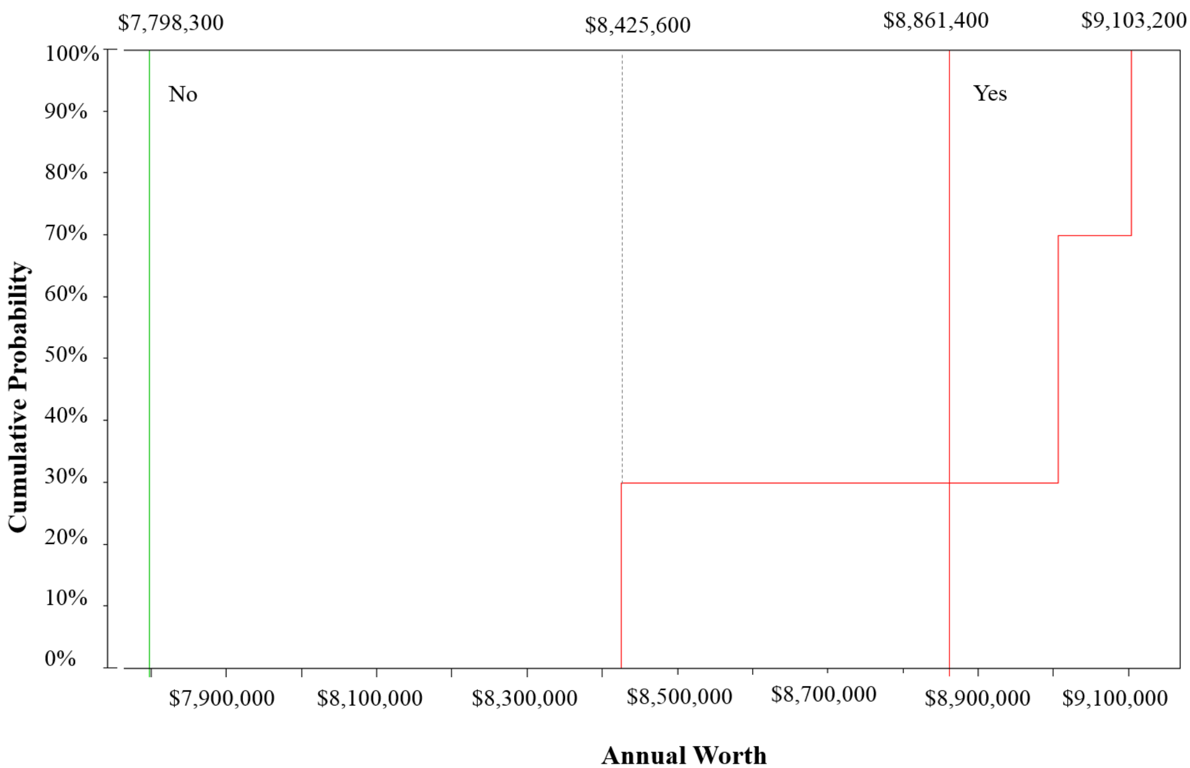

Figure 8.8: DPL Risk Curve for Wilton Transportation Network AW Including Uncertainty

In Figure 8.8 the risk curve illustrates that if the event of the increase in gravel material costs occurs, then the network AW would be expected to be $1,063,100[59] per year more than if the event does not occur. In the case of the event of increasing gravel costs the RM of Wilton would need to plan for an increased network AW, on average over the planning period, of 14%.

[59] AW (Base Case) – AW (Gravel Costs Increase) = $8,861,400 - $7,798,300 = $1,063,100.

8.5 Levels of Service

With the network AW defined for the event of the increase in gravel material costs, the next piece of information required to support informed decision making was the impact to the levels of service. As with the previous examples the first level of service used was the network financial sustainability indicator (Annual Budget / AW). For this case study it was determined, through discussion with the RM, that the second level of service to be measured was the frequency of blading of the roads. The base levels of service are illustrated in Figure 8.9.

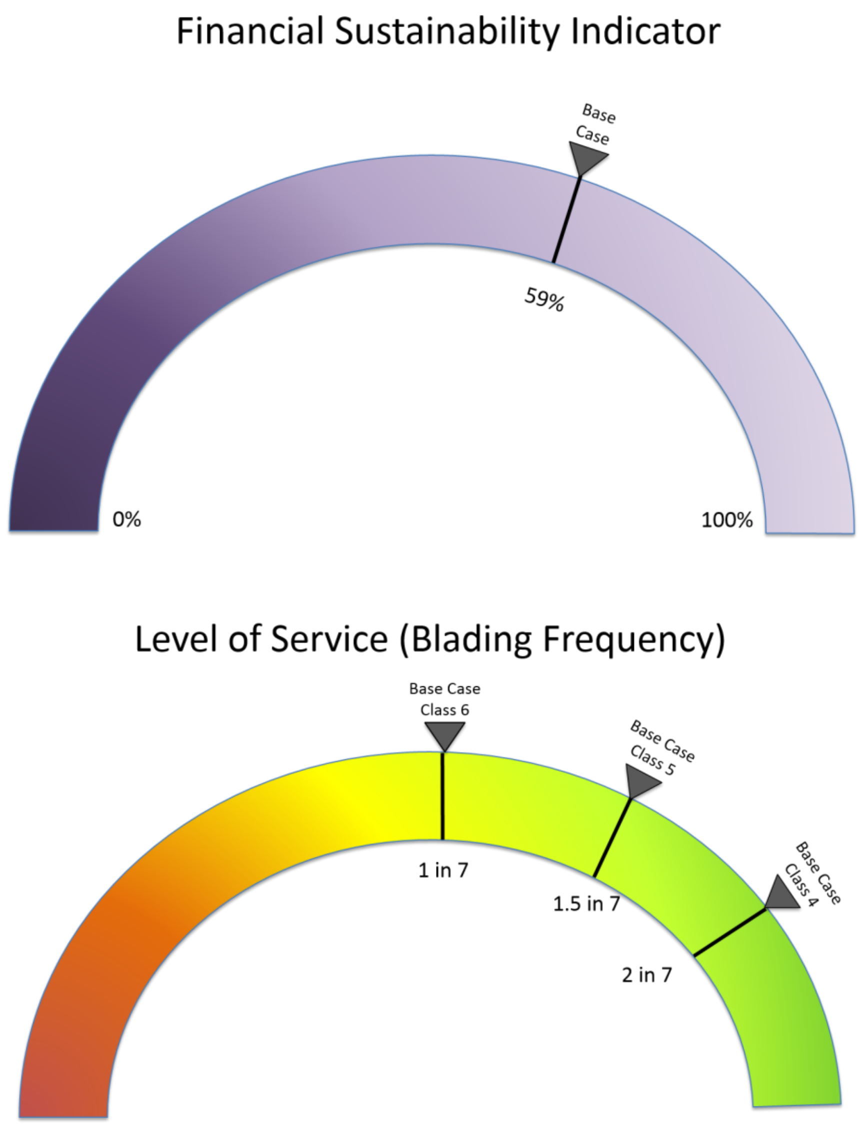

Figure 8.9: Levels of Service for Wilton Gravel Road Network Base Case

The base case levels of service provide a set point against which to compare the impact of the occurrence of the event of increasing gravel costs. The network financial sustainability indicator for the base case was calculated as 59%[60]. The second measured level of service was the frequency in blading (measured as the number of times per week that the roads were bladed). Currently the gravel road network was being bladed with a frequency based on the road class. The Wilton Class 4 roads are bladed 2 times per week, the Class 5 roads are bladed 1.5 times per week, and the Class 6 roads are bladed 1 time per week.

With the base levels of service defined it was possible to compare the impact given the event of the gravel costs increasing against the levels of service if the event does not occur. It is important that any discussion regarding potential event outcomes also discuss the potential impacts on the levels of service. The revised levels of service are illustrated in Figure 8.10.

The network financial sustainability indicator level of service was sensitive to the occurrence of the increasing material costs event. This event would impact the network financial sustainability indicator in a negative way. As with the previous examples there is risk in the potential outcome for the network AW which would directly impact this level of service. The risk is included in the level of service diagram through the use of a triangular distribution[61]. This allows both the expected value for the level of service (network financial sustainability indicator) to be illustrated, as well as the associated risk. If the event (rising gravel costs) were to occur the network financial sustainability indicator would have an expected value of 52% (shown on the level of service with a straight dashed line), with potential outcomes ranging from 51-55% (shown with the triangular distribution in dashed lines). The second level of service indicator that was used for this case study was the frequency of blading. Based on the occurrence of the event of increased gravel costs, it was not anticipated that the frequency of balding of the roads would be directly impacted. While the RM might reduce the levels of service to address the increasing costs, these would not be direct impacts due to the risk scenario.

[60] Sustainability Indicator = Annual Budget / AW * 100% = $4,621,300 / $7,798,300 * 100% = 59%
[61] A triangular distribution was shown for illustrative purposes only, the type of distribution would be dependent on the event.

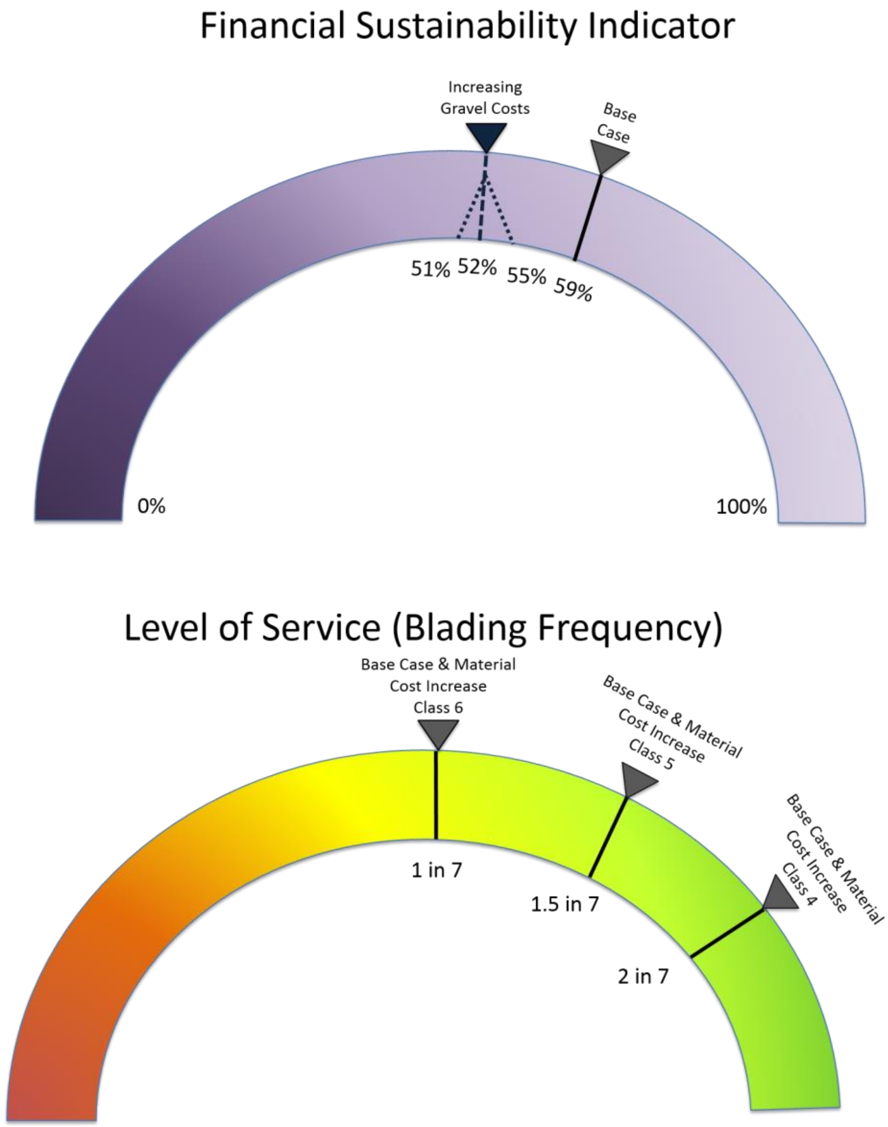

Figure 8.10: Levels of Service for Wilton Gravel Road Network Increasing Costs Scenario

8.6 Summary

This case study looked at the implications of the occurrence of the event of increasing gravel material costs on the RM of Wilton gravel road network. The RM has approximately 600 km's of gravel roads within their transportation network. Due to increasing scarcity of gravel the costs are increasing due to both increased material costs as well as further, more expensive, hauls of the material. The RM utilizes gravel for both operating and maintenance activities and renewals of the road assets. The increasing costs have begun to impact the funds required to maintain the gravel road network. However, the impact has not been defined in a way that included the uncertainty in the increase in costs. It would support informed decision making if there was better understanding of the potential event outcomes resulting from increased gravel costs. The implications of increasing gravel costs needed to address impacts to both the network AW and the levels of service.

This case study demonstrated how the model developed and utilized for the hypothetical network in previous chapters could be applied to a real life scenario to support informed decision making. The first aspect of the case study was to define the network AW for the base case. Through consultation with staff, the base case network AW was calculated as $7,798,300 per year[62]. This case study differed from the hypothetical example as the model was applied to an existing, as opposed to a proposed, network.

Once the base case network AW and levels of service were defined, the event of increasing gravel costs was analyzed. If the gravel costs were to increase, there was uncertainty as to the magnitude of the increase. The annual increase in gravel costs could range from 2-10% per year, but the expected increase was 7% per year. This forecasted increase was capped at a maximum of 300% as it was assumed that at this threshold current methods would be replaced with new materials, new technology, or new sources. The event outcomes of the increasing gravel costs were calculated, and illustrated that if the gravel costs did increase than the expected network AW would be $8,861,400 per year, however, there was risk that it could range from $8,425,600 to $9,103,200 per year. The expected network AW with the occurrence of increasing gravel costs was $1,063,100 per year more than if the gravel costs did not increase. This would result in a 14% increase in the network AW.

The levels of service that were used for this case study were the network financial sustainability indicator and the frequency of blading. It was determined that the first level of service (network financial sustainability indicator) was sensitive to the event, however, the second level of service (frequency of blading) was not directly (although it was potentially indirectly) impacted by increasing gravel costs. Although the frequency of blading was not sensitive to the event occurring it was determined to be a critical component of the level of service discussion, and

[62] For the AW calculation a discount rate of 4% and a study period of 70 years was used.

as such was still included. If the event occurred (increasing gravel costs) then the network financial sustainability indicator would be expected to decrease from 59% (if gravel costs did not increase) to 52%. There was risk in the outcome of the network financial sustainability indicator given the increase in gravel costs as it had potential outcomes ranging from 51% to 55%.

For decision makers this case study illustrated how the implications of the occurrence of an event, such as increasing gravel costs, can be quantified in terms of network AW and levels of service in a credible and transparent way that can be effectively communicated. Having information regarding the potential impacts of network variable uncertainty on the network AW, and levels of service, allows decision makers to make fully informed decisions in the face of uncertainty.

CHAPTER 9 CONCLUSIONS

9.1 Summary

The management of infrastructure networks is critical for municipal entities. This management has become increasingly difficult due to additional downloaded infrastructure from upper tiers of government, aging infrastructure, increased expectations for levels of service, and increased demand to demonstrate value for money. While there are local and international standards to support the effective management of infrastructure, few if any of these standards explicitly address the financial implications that result from the uncertainty associated with the management of this infrastructure.

Without credibly quantifying the potential implications of network variable uncertainty, and including this uncertainty in estimates of financial requirements, infrastructure management systems may actually regularly and significantly over or under estimate the actual financial requirements required. Without quantifying and including the uncertainty within the financial requirements of managing an infrastructure network, these estimates of financial requirements may actually include a systematic bias.

The objective of this research was to illustrate and quantify that IAM planning without accounting for network variable uncertainty, such as (1) changing technology, (2) changing standards, (3) increasing material costs, and (4) extreme weather events, could lead to systematic under or over estimates of infrastructure financial requirements and lead to decisions not necessarily in the best interests of the municipality.

A model was developed to demonstrate how network variable uncertainty could be included in financial planning for infrastructure networks. The model was able to: (1) be applied to various types of infrastructure networks, (2) incorporate network variable uncertainty, (3) compare alternatives and scenarios, and (4) support effective communication of results. The outputs of the model were the average network annual worth (AW) and network present worth (PW). These outputs, along with tornado plots, risks curves, level of service dashboards, and existing budget levels, were used to communicate the impacts of the network variable uncertainty on the financial projections. The model was developed using Excel tools linked to DPL software to utilize probabilistic methods. The Life Cycle Cost (LCC) portion of the model was successfully verified against an existing infrastructure costing tool, the Land and Infrastructure Resiliency Assessment (LIRA) tool developed by the Agri-Environmental Services Branch of Agriculture and Agri-Food Canada. The impact of the network variable uncertainty within the variables was also quantified in terms of levels of service provided by the organization.

The developed model was first applied to a hypothetical road network. For the hypothetical rural road network there were four events, representing network variable uncertainty, that were considered. These decisions or events included the: (1) decision to implement a new technology, (2) event of changing standards, (3) event of increased material costs, and (4) occurrence of a rainfall event. The hypothetical network illustrated that if the defined events occurred, then the expected network AW would increase from $481,400 per year (with no events occurring) to $678,900 per year. The expected network AW was $197,500 per year more when the events occurred. This is an increase of 41% in the anticipated network AW.

The impacts of decisions or events on the hypothetical network levels of service, stemming from network variable uncertainty, were also considered. The measured levels of service for the hypothetical network included the network financial sustainability indicator (an indicator reflecting the network current budget divided by the network annual worth as a percentage) and the frequency of blading of the roads. It was determined that the first level of service (the network financial sustainability indicator) was sensitive to the occurrence of the events. If the events occur, then the network sustainability indicator would be expected to decrease from 77% (if the events do not occur) to 54% if the uncertainty events are included. There was risk in the outcome of the network financial sustainability indicator which could potentially vary from 45-68%. The frequency of the blading of the gravel road level of service was only sensitive to the event of changing standards. Given the event of changing standards (due to increased usage) the frequency of blading was expected to increase from 1 time per week (with no changing standards) to 2 times per week. There was risk in this level of service as well with the frequency of blading potentially ranging from 1 time per week to 2 times per week.

The hypothetical network showed that the LCC model could incorporate network variable uncertainty using probabilistic methods. It also demonstrated that the event outcomes, resulting from the uncertainty, could be communicated in a meaningful way using LCC profiles, tornado plots, risk curves, and level of service dashboards.

The first case study was the Town of Shellbrook sanitary main network. The network variable uncertainty for the case study resulted from the potential decision to implement a new trenchless technology for the renewal of sanitary mains. The new technology was expected to decrease the renewal costs along with having a shorter expected useful lives. However, there was uncertainty as to what percentage of the sanitary mains would be found to be suitable for the new technology. It was anticipated that 70% of the mains would be suitable for relining, however, there was a possibility that it could be as little as 0% or as high as 100% of the network. The base case network AW was calculated as $716,900 per year. If the decision was made to implement the new technology the network AW had an expected value of $593,400. This means that the decision to implement the new technology was expected to result in a 17% reduction in the network AW. Since there was uncertainty in the decision to implement the new technology the potential event outcomes (network AW) ranged from $503,900-$716,900 per year.

The levels of service that were used for the Shellbrook case study were the network financial sustainability indicator and the meeting of standards set by regulating bodies. It was determined that the network financial sustainability indicator was sensitive to the decision, while the meeting of regulating bodies was not. If the decision was made to implement the new technology the network sustainability indicator would be expected to increase from 28% (if the new technology was not implemented) to 34%. There was risk in the outcome of the network financial sustainability indicator which could vary from 28-40%.

An important aspect raised during the Shellbrook case study was the use of upcoming work for an existing network that is partway through its life cycle. This can be an important consideration as infrastructure expenditure tends to go through peaks and troughs based on periods of high and low renewals. By looking at upcoming network expenditures based on asset age and condition, more informed long term planning can be completed.

The second case study was the RM of Wilton gravel road network. The network variable uncertainty for this case study resulted from the potential increase in gravel material costs. The RM has experienced increased gravel costs over the past number of years, however, the increase in costs has been highly variable. The network variable uncertainty was a result of uncertainty in the magnitude of the annual increase in gravel costs. The expected increase in gravel costs was 7% per year, however, it was anticipated that it could be as low as 2% or as high as 10% per year. The increase in the gravel costs was capped at an increase of 300%. The increase in gravel costs was capped as it was determined that at a certain threshold current methods would be replaced with new materials, new technology, or new sources. The base case network AW was calculated as $7,798,300 per year. Given the event of increasing gravel costs the expected network AW would be increased to $8,861,400 per year. This means that the event of increasing gravel costs would increase the expected network AW by 14%. Since there was uncertainty in the event of increasing gravel costs, the potential event outcomes (network AW) ranged from $8,425,600 to $9,103,200 per year.

The levels of service indicators used for the RM of Wilton case study were the network financial sustainability indicator and the frequency of blading. It was determined that the network financial sustainability indicator was sensitive to the event (increasing gravel costs), while the frequency of blading was not directly impacted (although it may be indirectly impacted). If the event of increasing gravel costs were to occur then the network financial sustainability indicator would be expected to decrease from 59% (if gravel costs did not increase) to 52%. There was risk in the outcome of the network financial sustainability indicator given the increase in gravel costs as it had potential outcomes ranging from 51% to 55%. Although the frequency of blading was not sensitive to the event occurring it was determined to be a critical component of the level of service discussion, and as such was still included.

The case studies illustrated that without considering network variable uncertainty, infrastructure managers may introduce a systematic bias into long term planning. Network variable uncertainty can significantly impact the projected expenditures estimated for the long term provision of services. Infrastructure managers and decision makers need to manage infrastructure in a sustainable way over the long term in the face of uncertainty. It is necessary that managers have information regarding the impacts of network variable uncertainty on both LCCs and levels of service to best provide value for money in managing infrastructure networks.

9.2 Conclusions

This research proved that the hypothesis was correct. A model was developed that quantified and communicated the financial implications and level of service impacts of network variable uncertainty for IAM planning. This research illustrated and quantified that IAM planning without accounting for network variable uncertainty, such as: (1) changing technology, (2) changing standards, (3) increasing material costs, and (4) extreme weather events, managers may introduce a systematic bias into long term planning. Network variable uncertainty has the potential to significantly impact the projected expenditures required for the long term provision of services. Infrastructure managers and decision makers need to manage infrastructure in a sustainable way over the long term in the face of uncertainty. It is necessary that decision makers have information regarding the impacts of network variable uncertainty on both LCCs and levels of service to make fully informed decision.

The goal of this research, to demonstrate that ignoring network variable uncertainty could lead to systematic over or under estimates of the financial requirements, was achieved by accomplishing three objectives. The first objective was that a probabilistic model could be developed to estimate network LCCs. This objective was achieved through the development of an excel model which was linked to DPL. The probabilistic model was applicable to various types of infrastructure networks and was verified using the LIRA tool. The second objective was to illustrate the significance of network variable uncertainties within IAM planning using Saskatchewan case studies. This was achieved by applying the developed model to two case studies, the Town of Shellbrook sanitary sewer network, and the RM of Wilton gravel road network. The results of the case studies demonstrated that the inclusion of network variable uncertainty could lead to a reduction (implementation of new technology) or an increase (increasing material costs) in the expected network AW in the order of 10-20%. The third objective was a discussion regarding how network variable uncertainty may impact decision making. This was demonstrated through the link of LCCs to impacts on levels of service as well as the risk associated with expected outcomes.

9.3 Future Work

This research has looked at the inclusion of network variable uncertainty within the IAM framework to support informed decision making. This work was a first step in establishing the processes that could be used to include network variable uncertainty in a credible and transparent way. This process could form a foundation for future research. Some potential avenues for building upon this work include, but are not limited to:

1) The proposal of consistent levels of service that could be used by multiple organizations,

2) An expansion on the potential levels of service that could be included,

3) A review of financial projections using methods other than the network AW (such as long term financial plans),

4) A review and summary of local unit rates to better forecast LCCs,

5) Establishing direct linkages to risk management methods, including concepts such as value of information and value of control, and

6) Robust links to tools used for estimating potential impacts of extreme weather events.

7) Links to technical infrastructure performance tools.

The practice of IAM has become more common in recent time due to the necessity of the information that it provides for the management process. It is anticipated that this area of research will significantly develop and expand in coming years.

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APPENDIX A

MODEL VERIFICATION TO LIRA TOOL

Figure A-1: LIRA Study Definition

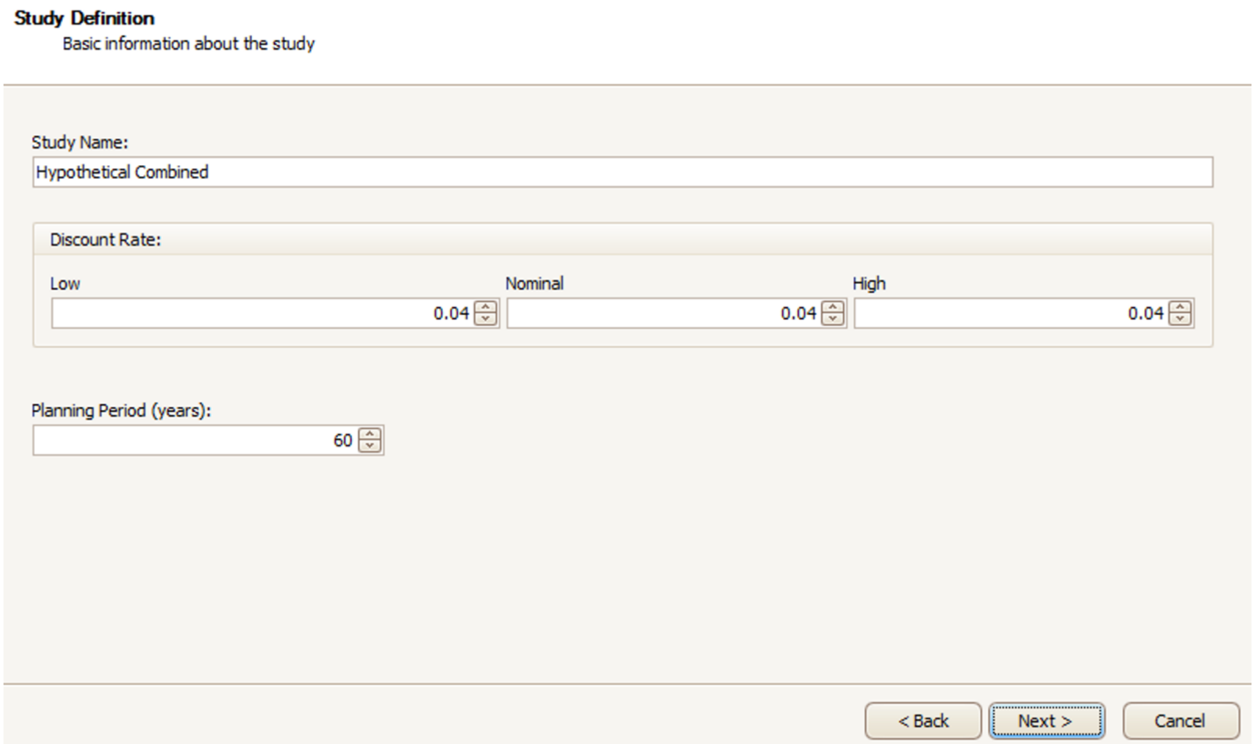
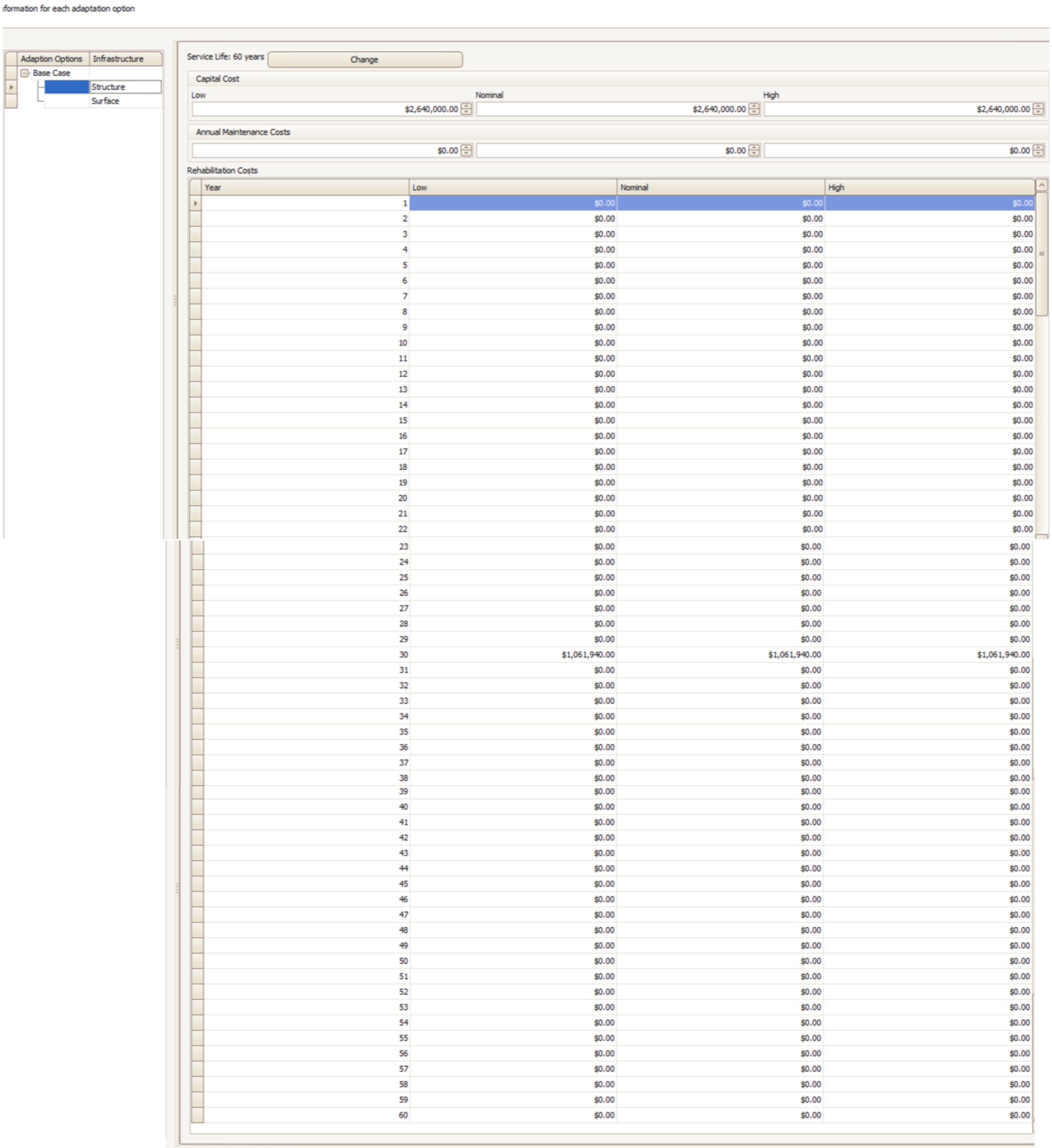


Figure A-2: LIRA Road Structure LCCs



formation for each adaptation option

Adaption Options	Infrastructure
Base Case	
	Structure
	Surface

Service Life: 60 years Change

Capital Cost

Low	Nominal	High
$2,640,000.00	$2,640,000.00	$2,640,000.00

Annual Maintenance Costs

$0.00	$0.00	$0.00

Rehabilitation Costs

Year	Low	Nominal	High
1	$0.00	$0.00	$0.00
2	$0.00	$0.00	$0.00
3	$0.00	$0.00	$0.00
4	$0.00	$0.00	$0.00
5	$0.00	$0.00	$0.00
6	$0.00	$0.00	$0.00
7	$0.00	$0.00	$0.00
8	$0.00	$0.00	$0.00
9	$0.00	$0.00	$0.00
10	$0.00	$0.00	$0.00
11	$0.00	$0.00	$0.00
12	$0.00	$0.00	$0.00
13	$0.00	$0.00	$0.00
14	$0.00	$0.00	$0.00
15	$0.00	$0.00	$0.00
16	$0.00	$0.00	$0.00
17	$0.00	$0.00	$0.00
18	$0.00	$0.00	$0.00
19	$0.00	$0.00	$0.00
20	$0.00	$0.00	$0.00
21	$0.00	$0.00	$0.00
22	$0.00	$0.00	$0.00
23	$0.00	$0.00	$0.00
24	$0.00	$0.00	$0.00
25	$0.00	$0.00	$0.00
26	$0.00	$0.00	$0.00
27	$0.00	$0.00	$0.00
28	$0.00	$0.00	$0.00
29	$0.00	$0.00	$0.00
30	$1,061,940.00	$1,061,940.00	$1,061,940.00
31	$0.00	$0.00	$0.00
32	$0.00	$0.00	$0.00
33	$0.00	$0.00	$0.00
34	$0.00	$0.00	$0.00
35	$0.00	$0.00	$0.00
36	$0.00	$0.00	$0.00
37	$0.00	$0.00	$0.00
38	$0.00	$0.00	$0.00
39	$0.00	$0.00	$0.00
40	$0.00	$0.00	$0.00
41	$0.00	$0.00	$0.00
42	$0.00	$0.00	$0.00
43	$0.00	$0.00	$0.00
44	$0.00	$0.00	$0.00
45	$0.00	$0.00	$0.00
46	$0.00	$0.00	$0.00
47	$0.00	$0.00	$0.00
48	$0.00	$0.00	$0.00
49	$0.00	$0.00	$0.00
50	$0.00	$0.00	$0.00
51	$0.00	$0.00	$0.00
52	$0.00	$0.00	$0.00
53	$0.00	$0.00	$0.00
54	$0.00	$0.00	$0.00
55	$0.00	$0.00	$0.00
56	$0.00	$0.00	$0.00
57	$0.00	$0.00	$0.00
58	$0.00	$0.00	$0.00
59	$0.00	$0.00	$0.00
60	$0.00	$0.00	$0.00

Figure A-3: LIRA Road Surface LCCs

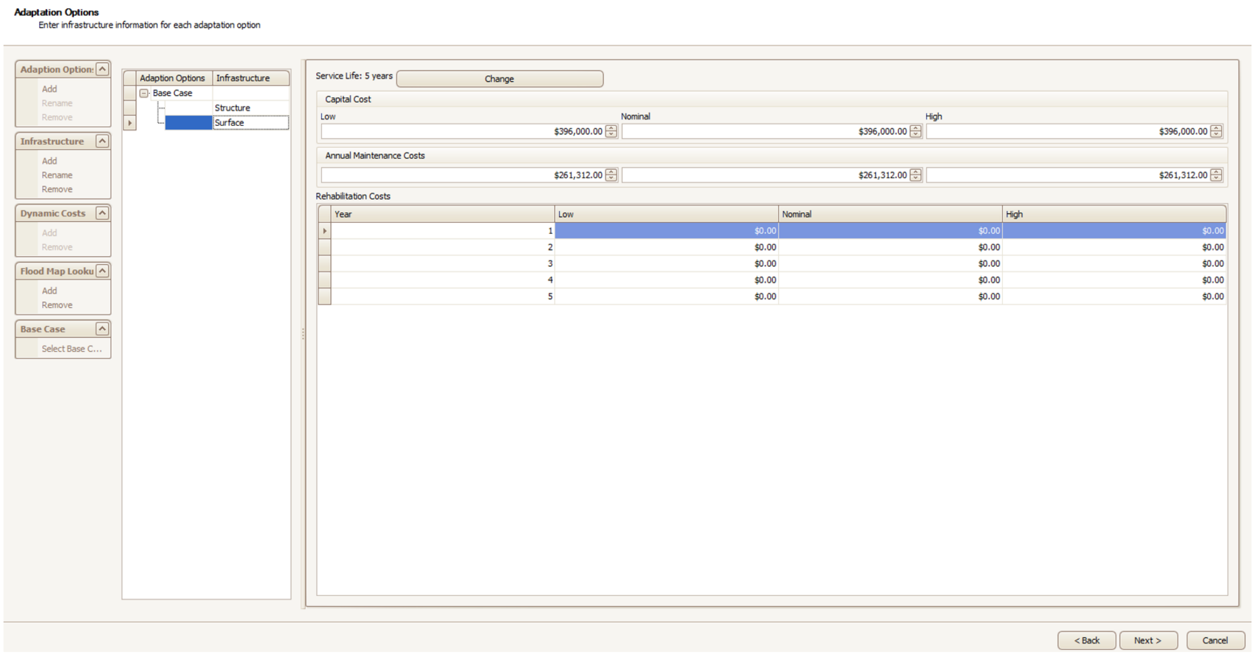
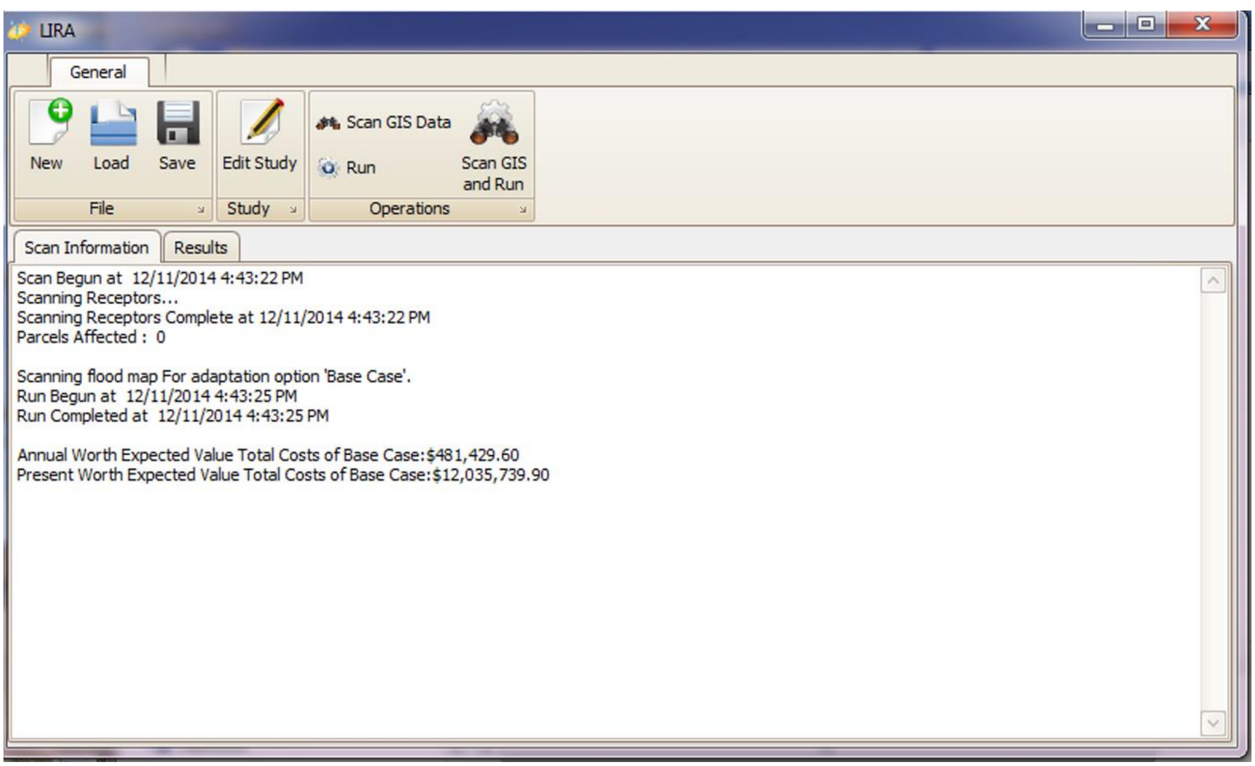


Figure A-4: LIRA Model Outputs



APPENDIX B

HYPOTHETICAL NETWORK DATA

Table B-1: Hypothetical Network Asset Register

Asset ID	Asset Name	Descriptor 1	Descriptor 2	Year of Construction	Useful Life	Length	Unit
Road 1-a	Structure	Second Street	Second Avenue to Third Avenue	1965	60	1	km
Road 1-b	Surface	Second Street	Second Avenue to Third Avenue	2013	5	1	km
Road 2-a	Structure	Second Avenue	First Street to Second Street	1965	60	1	km
Road 2-b	Surface	Second Avenue	First Street to Second Street	2013	5	1	km
Road 3-a	Structure	Second Avenue	Second Street to Third Street	1965	60	1	km
Road 3-b	Surface	Second Avenue	Second Street to Third Street	2013	5	1	km
Road 4-a	Structure	Second Street	First Avenue to Second Avenue	1965	60	1	km
Road 4-b	Surface	Second Street	First Avenue to Second Avenue	2013	5	1	km
Road 5-a	Structure	Second Street	First Avenue to Second Avenue	1965	60	1	km
Road 5-b	Surface	Second Street	First Avenue to Second Avenue	2013	5	1	km
Road 6-a	Structure	Second Street	First Avenue to Second Avenue	1965	60	1	km
Road 6-b	Surface	Second Street	First Avenue to Second Avenue	2013	5	1	km
Road 7-a	Structure	Second Street	First Avenue to Second Avenue	1965	60	1	km
Road 7-b	Surface	Second Street	First Avenue to Second Avenue	2013	5	1	km
Road 8-a	Structure	Second Street	First Avenue to Second Avenue	1965	60	1	km
Road 8-b	Surface	Second Street	First Avenue to Second Avenue	2013	5	1	km
Road 9-a	Structure	Second Street	First Avenue to Second Avenue	1965	60	1	km
Road 9-b	Surface	Second Street	First Avenue to Second Avenue	2013	5	1	km
Road 10-a	Structure	Second Street	First Avenue to Second Avenue	1965	60	1	km
Road 10-b	Surface	Second Street	First Avenue to Second Avenue	2013	5	1	km
Road 11-a	Structure	Second Street	First Avenue to Second Avenue	1965	60	1	km

Road 11-b	Surface	Second Street	First Avenue to Second Avenue	2013	5	1	km
Road 12-a	Structure	Second Street	First Avenue to Second Avenue	1965	60	1	km
Road 12-b	Surface	Second Street	First Avenue to Second Avenue	2013	5	1	km

Table B-2: Hypothetical Network Operation and Maintenance Activities

	Annual frequency	**Unit**	**Total Unit Cost**
Grading - 1-7	52	per km/yr	$9,000
Gravelling	1	per km/yr	$7,400
Shoulder Pulling	2	per km/yr	$1,300
Dust Control	5	per km/yr	$4,200

Table B-3: Hypothetical Network Gravel Index

Year	At No Gravel Cost Increase	At 2% Gravel Cost Increase	At 5% Gravel Cost Increase	At 10% Gravel Cost Increase
0	100%	100%	100%	100%
1	100%	102%	105%	110%
2	100%	104%	110%	121%
3	100%	106%	116%	133%
4	100%	108%	122%	146%
5	100%	110%	128%	161%
6	100%	113%	134%	177%
7	100%	115%	141%	195%
8	100%	117%	148%	214%
9	100%	120%	155%	236%
10	100%	122%	163%	259%
11	100%	124%	171%	285%
12	100%	127%	180%	300%
13	100%	129%	189%	300%
14	100%	132%	198%	300%
15	100%	135%	208%	300%
16	100%	137%	218%	300%
17	100%	140%	229%	300%
18	100%	143%	241%	300%
19	100%	146%	253%	300%
20	100%	149%	265%	300%
21	100%	152%	279%	300%
22	100%	155%	293%	300%
23	100%	158%	300%	300%
24	100%	161%	300%	300%
25	100%	164%	300%	300%
26	100%	167%	300%	300%
27	100%	171%	300%	300%
28	100%	174%	300%	300%
29	100%	178%	300%	300%
30	100%	181%	300%	300%
31	100%	185%	300%	300%
32	100%	188%	300%	300%
33	100%	192%	300%	300%
34	100%	196%	300%	300%
35	100%	200%	300%	300%
36	100%	204%	300%	300%
37	100%	208%	300%	300%

38	100%	212%	300%	300%
39	100%	216%	300%	300%
40	100%	221%	300%	300%
41	100%	225%	300%	300%
42	100%	230%	300%	300%
43	100%	234%	300%	300%
44	100%	239%	300%	300%
45	100%	244%	300%	300%
46	100%	249%	300%	300%
47	100%	254%	300%	300%
48	100%	259%	300%	300%
49	100%	264%	300%	300%
50	100%	269%	300%	300%
51	100%	275%	300%	300%
52	100%	280%	300%	300%
53	100%	286%	300%	300%
54	100%	291%	300%	300%
55	100%	297%	300%	300%
56	100%	300%	300%	300%
57	100%	300%	300%	300%
58	100%	300%	300%	300%
59	100%	300%	300%	300%
60	100%	300%	300%	300%

Table B-4: Influence Model Variable Values and Associated Probabilities

	Base Case	*Including Uncertainty*		
		Low Value	*Nominal Value*	*High Value*
Event Year	Event does not occur in study period.	Event occurs in Year 1 *Probability = 30%*	Event occurs in Year 100 *Probability = 40%*	Event occurs in Year 500 *Probability = 30%*
Technology Index	Technology is not implemented	15% Reduction in Renewal Costs *Probability = 30%*	20% Reduction in Renewal Costs *Probability = 40%*	25% Reduction in Renewal Costs *Probability = 30%*
Technology Useful Life	60 years	50 years *Probability = 30%*	55 years *Probability = 40%*	60 years *Probability = 30%*
Grading Index	Roads are graded 1 in 7 days	Roads are graded 1 in 7 days *Probability = 30%*	Roads are graded 1.5 in 7 days *Probability = 40%*	Roads are graded 2 in 7 days *Probability = 30%*
Gravel Index	Gravel costs do not increase	2% Annual Increase *Probability = 30%*	5% Annual Increase *Probability = 30%*	10% Annual Increase *Probability = 30%*

Figure B-1: Hypothetical Proposed Network Full Life Cycle Cost Profile – No Uncertainty

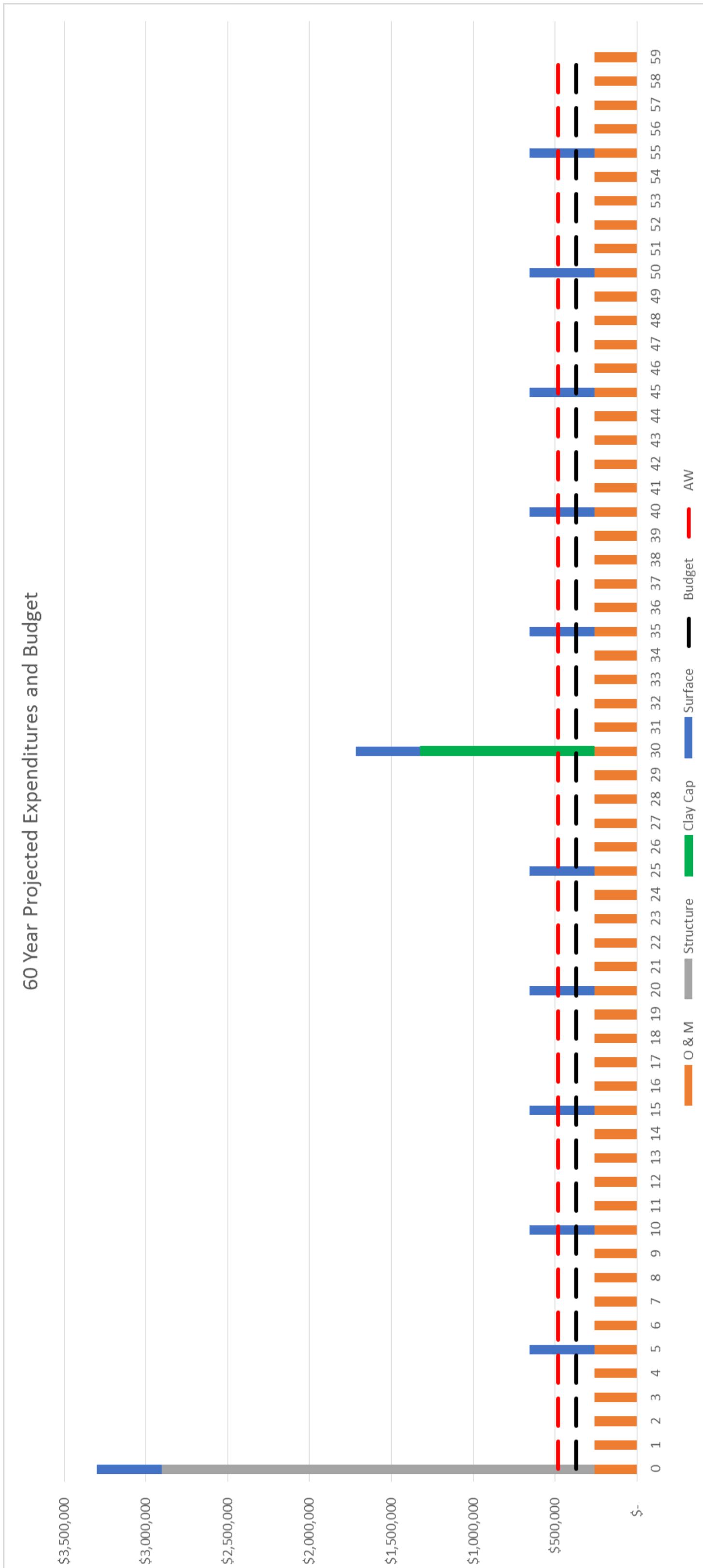
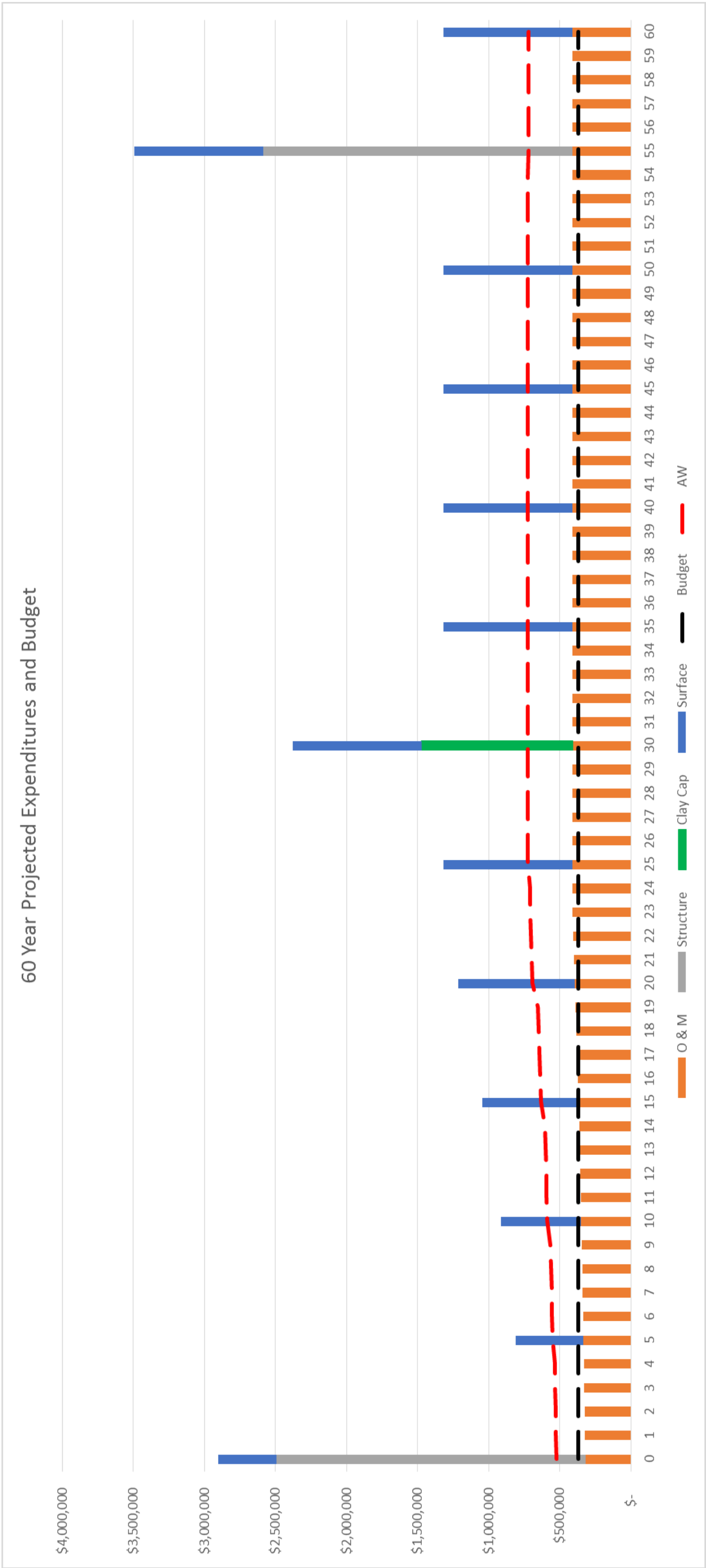


Figure B-2: Hypothetical Proposed Network Full Life Cycle Cost Profile – Including Uncertainty at Expected Values



APPENDIX C

TOWN OF SHELLBROOK DATA

Table C-1: Town of Shellbrook Asset Register

Asset ID	Asset Type	Asset Name	Current Pipe Status	Year of Construction	Useful Life	Length	Unit
SSLine-001	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	12.1	m
SSLine-002	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	95.2	m
SSLine-003	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	123.9	m
SSLine-004	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	98.4	m
SSLine-005	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	104	m
SSLine-006	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	27.5	m
SSLine-007	Sanitary Main	200 PVC	Not lined	1980	60	59.9	m
SSLine-008	Sanitary Main	200 PVC	Not lined	1980	60	65.7	m
SSLine-009	Sanitary Main	200 PVC	Not lined	1980	60	63.5	m
SSLine-010	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	49.9	m
SSLine-011	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	58.1	m
SSLine-012	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	17.5	m
SSLine-013	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	70.7	m
SSLine-014	Sanitary Main	200 PVC	Not lined	1980	60	136.1	m
SSLine-015	Sanitary Main	200 PVC	Not lined	1980	60	84.4	m
SSLine-016	Sanitary Main	200 PVC	Not lined	1980	60	73.2	m
SSLine-017	Sanitary Main	200 PVC	Not lined	1980	60	71.4	m
SSLine-018	Sanitary Main	200 PVC	Not lined	1980	60	3.3	m
SSLine-019	Sanitary Main	200 PVC	Not lined	1980	60	89.3	m
SSLine-020	Sanitary Main	200 PVC	Not lined	1980	60	48.5	m
SSLine-021	Sanitary Main	200 PVC	Not lined	1986	60	91.1	m
SSLine-022	Sanitary Main	200 PVC	Not lined	1986	60	92.1	m
SSLine-023	Sanitary Main	200 PVC	Not lined	1980	60	155.7	m
SSLine-024	Sanitary Main	100 PVC	Not lined	1986	60	31.1	m
SSLine-025	Sanitary Main	100 PVC	Not lined	1980	60	45.5	m
SSLine-026	Sanitary Main	200 PVC	Not lined	1980	60	76.2	m
SSLine-027	Sanitary Main	200 PVC	Not lined	1980	60	22.9	m
SSLine-028	Sanitary Main	200 PVC	Not lined	1980	60	122.7	m
SSLine-029	Sanitary Main	50 PVC	Not lined	1980	60	155.4	m
SSLine-030	Sanitary Main	200 PVC	Not lined	1980	60	109.1	m
SSLine-031	Sanitary Main	200 PVC	Not lined	1980	60	97.3	m
SSLine-032	Sanitary Main	200 PVC	Not lined	1980	60	103.7	m
SSLine-033	Sanitary Main	200 PVC	Not lined	1980	60	97.8	m
SSLine-034	Sanitary Main	200 PVC	Not lined	1980	60	92	m
SSLine-035	Sanitary Main	200 PVC	Not lined	1980	60	111	m
SSLine-036	Sanitary Main	200 PVC	Not lined	1980	60	90.8	m
SSLine-037	Sanitary Main	200 PVC	Not lined	1970	60	86.1	m

SSLine-038	Sanitary Main	200 PVC	Not lined	1970	60	81.1	m
SSLine-039	Sanitary Main	200 PVC	Not lined	1970	60	85.2	m
SSLine-040	Sanitary Main	200 PVC	Not lined	1979	60	66.1	m
SSLine-041	Sanitary Main	200 PVC	Not lined	1970	60	85	m
SSLine-042	Sanitary Main	200 PVC	Not lined	1979	60	98.1	m
SSLine-043	Sanitary Main	200 PVC	Not lined	1970	60	85	m
SSLine-044	Sanitary Main	200 PVC	Not lined	1979	60	61.5	m
SSLine-045	Sanitary Main	200 PVC	Not lined	1979	60	67.6	m
SSLine-046	Sanitary Main	200 PVC	Not lined	1970	60	88.3	m
SSLine-047	Sanitary Main	200 PVC	Not lined	1979	60	61.5	m
SSLine-048	Sanitary Main	200 PVC	Not lined	1979	60	58.8	m
SSLine-049	Sanitary Main	200 PVC	Not lined	1979	60	95.5	m
SSLine-050	Sanitary Main	200 PVC	Not lined	1979	60	58.9	m
SSLine-051	Sanitary Main	200 PVC	Not lined	1979	60	62	m
SSLine-052	Sanitary Main	200 PVC	Not lined	1970	60	95.6	m
SSLine-053	Sanitary Main	200 PVC	Not lined	1970	60	90.1	m
SSLine-054	Sanitary Main	200 PVC	Not lined	2000	60	60.8	m
SSLine-055	Sanitary Main	200 PVC	Not lined	2000	60	57.9	m
SSLine-056	Sanitary Main	200 PVC	Not lined	2000	60	96.8	m
SSLine-057	Sanitary Main	200 PVC	Not lined	2000	60	60.2	m
SSLine-058	Sanitary Main	200 PVC	Not lined	2000	60	59.5	m
SSLine-059	Sanitary Main	200 PVC	Not lined	1970	60	97.2	m
SSLine-060	Sanitary Main	200 PVC	Not lined	1970	60	11	m
SSLine-061	Sanitary Main	200 PVC	Not lined	2000	60	100.6	m
SSLine-062	Sanitary Main	200 PVC	Not lined	2000	60	84.3	m
SSLine-063	Sanitary Main	200 PVC	Not lined	1970	60	37.4	m
SSLine-064	Sanitary Main	200 PVC	Not lined	1970	60	42	m
SSLine-065	Sanitary Main	200 PVC	Not lined	2001	60	58.7	m
SSLine-066	Sanitary Main	200 PVC	Not lined	2001	60	58.7	m
SSLine-067	Sanitary Main	200 PVC	Not lined	2001	60	94.9	m
SSLine-068	Sanitary Main	200 PVC	Not lined	2001	60	94.9	m
SSLine-069	Sanitary Main	200 PVC	Not lined	2001	60	97	m
SSLine-070	Sanitary Main	200 PVC	Not lined	2001	60	62.1	m
SSLine-071	Sanitary Main	200 PVC	Not lined	1970	60	46.5	m
SSLine-072	Sanitary Main	200 PVC	Not lined	1970	60	46.5	m
SSLine-073	Sanitary Main	200 PVC	Not lined	2001	60	58.6	m
SSLine-074	Sanitary Main	200 PVC	Not lined	2001	60	58.6	m
SSLine-075	Sanitary Main	200 PVC	Not lined	2001	60	46.6	m
SSLine-076	Sanitary Main	200 PVC	Not lined	2001	60	46.6	m
SSLine-077	Sanitary Main	200 PVC	Not lined	2001	60	78	m
SSLine-078	Sanitary Main	200 PVC	Not lined	1970	60	55.3	m

SSLine-079	Sanitary Main	200 PVC	Not lined	2011	60	60.6	m
SSLine-080	Sanitary Main	200 PVC	Not lined	2011	60	18.2	m
SSLine-081	Sanitary Main	200 PVC	Not lined	2011	60	100.7	m
SSLine-082	Sanitary Main	200 PVC	Not lined	1970	60	99.9	m
SSLine-083	Sanitary Main	200 PVC	Not lined	2011	60	97.2	m
SSLine-084	Sanitary Main	200 PVC	Not lined	2011	60	77.9	m
SSLine-085	Sanitary Main	200 PVC	Not lined	2011	60	106.7	m
SSLine-086	Sanitary Main	200 PVC	Not lined	2011	60	46	m
SSLine-087	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	107.8	m
SSLine-088	Sanitary Main	250 PVC	Not lined	2008	60	65.5	m
SSLine-089	Sanitary Main	250 HDP	Not lined	2008	60	101.6	m
SSLine-090	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	89.2	m
SSLine-091	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	80	m
SSLine-092	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	88.9	m
SSLine-093	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	97.6	m
SSLine-094	Sanitary Main	250 Concrete / Clay	Not lined	1960	54	76.8	m
SSLine-095	Sanitary Main	200 Concrete / Clay	Not lined	1960	54	99.4	m
SSLine-096	Sanitary Main	200 Concrete / Clay	Not lined	1960	54	99.4	m
SSLine-097	Sanitary Main	200 Concrete / Clay	Not lined	1960	54	72.8	m
SSLine-098	Sanitary Main	200 Concrete / Clay	Not lined	1960	54	67.7	m
SSLine-099	Sanitary Main	200 PVC	Not lined	1980	60	85.4	m
SSLine-100	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	65.9	m
SSLine-101	Sanitary Main	200 Concrete / Clay	Not lined	1960	54	72.2	m
SSLine-102	Sanitary Main	200 Concrete / Clay	Not lined	1960	54	67.4	m
SSLine-103	Sanitary Main	100 PVC	Not lined	1980	60	46.9	m
SSLine-104	Sanitary Main	200 Concrete / Clay	Not lined	1960	55	107	m
SSLine-105	Sanitary Main	100 PVC	Not lined	1980	60	65.3	m
SSLine-106	Sanitary Main	250 Concrete / Clay	Not lined	1960	54	20.4	m
SSLine-107	Sanitary Main	250 PVC	Not lined	2010	60	83.3	m
SSLine-108	Sanitary Main	250 PVC	Not lined	2010	60	82.7	m
SSLine-109	Sanitary Main	250 Concrete / Clay	Not lined	1960	55	83.3	m
SSLine-110	Sanitary Main	250 Concrete / Clay	Not lined	1960	55	85.4	m
SSLine-111	Sanitary Main	250 Concrete / Clay	Not lined	1960	56	96.7	m
SSLine-112	Sanitary Main	200 Relined Concrete	Lined	2011	50	81.2	m
SSLine-113	Sanitary Main	200 PVC	Not lined	2011	60	69.8	m
SSLine-114	Sanitary Main	250 Concrete / Clay	Not lined	1960	56	99.4	m
SSLine-115	Sanitary Main	200 Concrete / Clay	Not lined	1960	57	72.2	m
SSLine-116	Sanitary Main	200 Concrete / Clay	Not lined	1960	57	78.8	m
SSLine-117	Sanitary Main	250 Concrete / Clay	Not lined	1960	56	99.4	m
SSLine-118	Sanitary Main	200 Concrete / Clay	Not lined	1960	57	81.2	m
SSLine-119	Sanitary Main	200 Concrete / Clay	Not lined	1960	57	69.8	m

SSLine-120	Sanitary Main	250 Concrete / Clay	Not lined	1960	58	99.4	m
SSLine-121	Sanitary Main	250 Concrete / Clay	Not lined	1960	58	82.9	m
SSLine-122	Sanitary Main	200 Concrete / Clay	Not lined	1960	59	85.4	m
SSLine-123	Sanitary Main	200 Concrete / Clay	Not lined	1960	59	83.3	m
SSLine-124	Sanitary Main	200 PVC	Not lined	1970	60	100.3	m
SSLine-125	Sanitary Main	200 PVC	Not lined	1970	60	101.6	m
SSLine-126	Sanitary Main	200 Concrete / Clay	Not lined	1960	59	85.4	m
SSLine-127	Sanitary Main	200 Concrete / Clay	Not lined	1960	60	83.3	m
SSLine-128	Sanitary Main	200 PVC	Not lined	1970	60	2.1	m
SSLine-129	Sanitary Main	200 PVC	Not lined	1970	60	49.1	m
SSLine-130	Sanitary Main	200 PVC	Not lined	1970	60	15.3	m
SSLine-131	Sanitary Main	200 Concrete / Clay	Not lined	1960	60	61.2	m
SSLine-132	Sanitary Main	200 Concrete / Clay	Not lined	1960	60	87.6	m
SSLine-133	Sanitary Main	200 Concrete / Clay	Not lined	1960	61	85.4	m
SSLine-134	Sanitary Main	200 Concrete / Clay	Not lined	1960	61	83.3	m
SSLine-135	Sanitary Main	200 Concrete / Clay	Not lined	1960	61	79	m
SSLine-136	Sanitary Main	200 Concrete / Clay	Not lined	1960	61	69.8	m
SSLine-137	Sanitary Main	250 HDP	Not lined	2008	60	85.4	m
SSLine-138	Sanitary Main	250 HDP	Not lined	2008	60	83.3	m
SSLine-139	Sanitary Main	250 HDP	Not lined	2008	60	83.3	m
SSLine-140	Sanitary Main	250 PVC	Not lined	2008	60	83.3	m
SSLine-141	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	99	m
SSLine-142	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	66.9	m
SSLine-143	Sanitary Main	250 PVC	Not lined	2008	60	107.1	m
SSLine-144	Sanitary Main	200 Relined Concrete	Lined	1960	65	99.5	m
SSLine-145	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	33.9	m
SSLine-146	Sanitary Main	250 PVC	Not lined	2008	60	10.2	m
SSLine-147	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	98.6	m
SSLine-148	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	101.5	m
SSLine-149	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	97	m
SSLine-150	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	5.8	m
SSLine-151	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	92.6	m
SSLine-152	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	102.3	m
SSLine-153	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	91.8	m
SSLine-154	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	104.6	m
SSLine-155	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	82.7	m
SSLine-156	Sanitary Main	200 PVC	Not lined	2000	60	93	m
SSLine-157	Sanitary Main	200 PVC	Not lined	2000	60	40.7	m
SSLine-158	Sanitary Main	200 PVC	Not lined	2000	60	53	m
SSLine-159	Sanitary Main	200 PVC	Not lined	2000	60	92.9	m
SSLine-160	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	89.5	m

SSLine-161	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	88.4	m
SSLine-162	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	102.7	m
SSLine-163	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	83.4	m
SSLine-164	Sanitary Main	250 PVC	Not lined	2008	60	102.8	m
SSLine-165	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	83.1	m
SSLine-166	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	83.3	m
SSLine-167	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	6	m
SSLine-168	Sanitary Main	200 Relined Concrete	Lined	1960	65	63.1	m
SSLine-169	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	133.6	m
SSLine-170	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	83.3	m
SSLine-171	Sanitary Main	200 PVC	Not lined	2007	60	101	m
SSLine-172	Sanitary Main	200 PVC	Not lined	2007	60	74	m
SSLine-173	Sanitary Main	200 PVC	Not lined	2007	60	70.1	m
SSLine-174	Sanitary Main	200 PVC	Not lined	2007	60	97.5	m
SSLine-175	Sanitary Main	200 PVC	Not lined	2007	60	103.2	m
SSLine-176	Sanitary Main	200 PVC	Not lined	2007	60	71.1	m
SSLine-177	Sanitary Main	200 PVC	Not lined	2007	60	69.8	m
SSLine-178	Sanitary Main	200 PVC	Not lined	2007	60	158.1	m
SSLine-179	Sanitary Main	200 PVC	Not lined	2007	60	83.2	m
SSLine-180	Sanitary Main	200 PVC	Not lined	2007	60	99.6	m
SSLine-181	Sanitary Main	200 PVC	Not lined	2007	60	155	m
SSLine-182	Sanitary Main	200 PVC	Not lined	2007	60	83.3	m
SSLine-183	Sanitary Main	200 PVC	Not lined	2007	60	86.4	m
SSLine-184	Sanitary Main	200 PVC	Not lined	2007	60	86.4	m
SSLine-185	Sanitary Main	200 PVC	Not lined	2008	60	50.2	m
SSLine-186	Sanitary Main	200 PVC	Not lined	2008	60	44.3	m
SSLine-187	Sanitary Main	200 PVC	Not lined	2008	60	100.3	m
SSLine-188	Sanitary Main	200 PVC	Not lined	2008	60	100.3	m
SSLine-189	Sanitary Main	200 Concrete / Clay	Not lined	1960	62	0.1	m
SSLine-190	Sanitary Main	200 Concrete / Clay	Not lined	1960	62	85.4	m
SSLine-191	Sanitary Main	200 Relined Concrete	Lined	2011	50	83.3	m
SSLine-192	Sanitary Main	200 Relined Concrete	Lined	2011	50	79.5	m
SSLine-193	Sanitary Main	200 Relined Concrete	Lined	2011	50	69.4	m
SSLine-194	Sanitary Main	250 Concrete / Clay	Not lined	1960	62	99.5	m
SSLine-195	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	78.3	m
SSLine-196	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	54.6	m
SSLine-197	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	59.7	m
SSLine-198	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	66.3	m
SSLine-199	Sanitary Main	200 Relined Concrete	Lined	1960	65	99.5	m
SSLine-200	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	78.1	m
SSLine-201	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	87.3	m

SSLine-202	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	139.7	m
SSLine-203	Sanitary Main	200 Concrete / Clay	Not lined	1960	65	58.8	m
SSLine-204	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	111.4	m
SSLine-205	Sanitary Main	250 Concrete / Clay	Not lined	1960	65	123.9	m
SSLine-206	Sanitary Main	250 PVC	Not lined	2009	60	112.1	m
SSLine-207	Sanitary Main	250 PVC	Not lined	2009	60	108.9	m
SSLine-208	Sanitary Main	200 PVC	Not lined	2009	60	112.8	m
SSLine-209	Sanitary Main	200 PVC	Not lined	2009	60	49.2	m
SSLine-210	Sanitary Main	200 PVC	Not lined	2009	60	84	m
SSLine-211	Sanitary Main	200 PVC	Not lined	2009	60	90.5	m
SSLine-212	Sanitary Main	200 PVC	Not lined	2009	60	90.5	m
SSLine-213	Sanitary Main	200 PVC	Not lined	2009	60	12.9	m
SSLine-214	Sanitary Main	200 PVC	Not lined	2009	60	136.3	m
SSLine-215	Sanitary Main	200 PVC	Not lined	2009	60	76.6	m
SSLine-216	Sanitary Main	250 PVC	Not lined	2008	60	55.9	m
SSLine-217	Sanitary Main	250 PVC	Not lined	2008	60	58.3	m
SSLine-218	Sanitary Main	250 PVC	Not lined	2008	60	93.8	m
SSLine-219	Sanitary Main	200 PVC	Not lined	2008	60	61.7	m
SSLine-220	Sanitary Main	200 PVC	Not lined	2012	60	1000	m
SSLine-221	Sanitary Main	200 PVC	Not lined	2012	60	1000	m
SSLine-222	Sanitary Main	200 PVC	Not lined	2013	60	50	m

Table C-2: Town of Shellbrook Operation and Maintenance Activities

	Annual Frequency	**Unit**	**Total Unit Cost**
Flushing	2	per m/yr	$30,000
Repairs	--	--	$24,000

Figure C-1: Town of Shellbrook Proposed Network Full Life Cycle Cost Profile – No Uncertainty

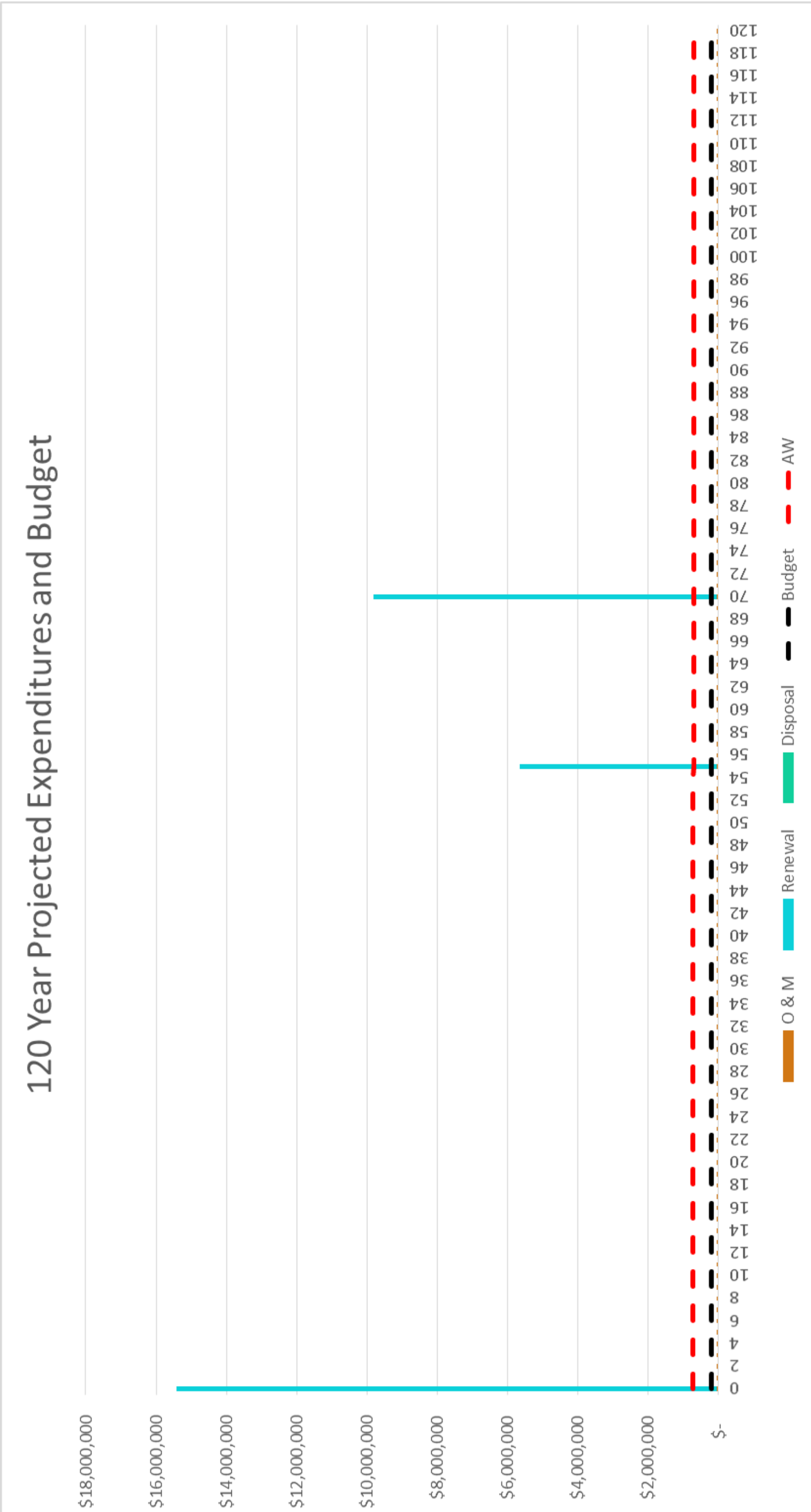


Figure C-2: Town of Shellbrook Proposed Network Full Life Cycle Cost Profile – Including Uncertainty at Expected Values

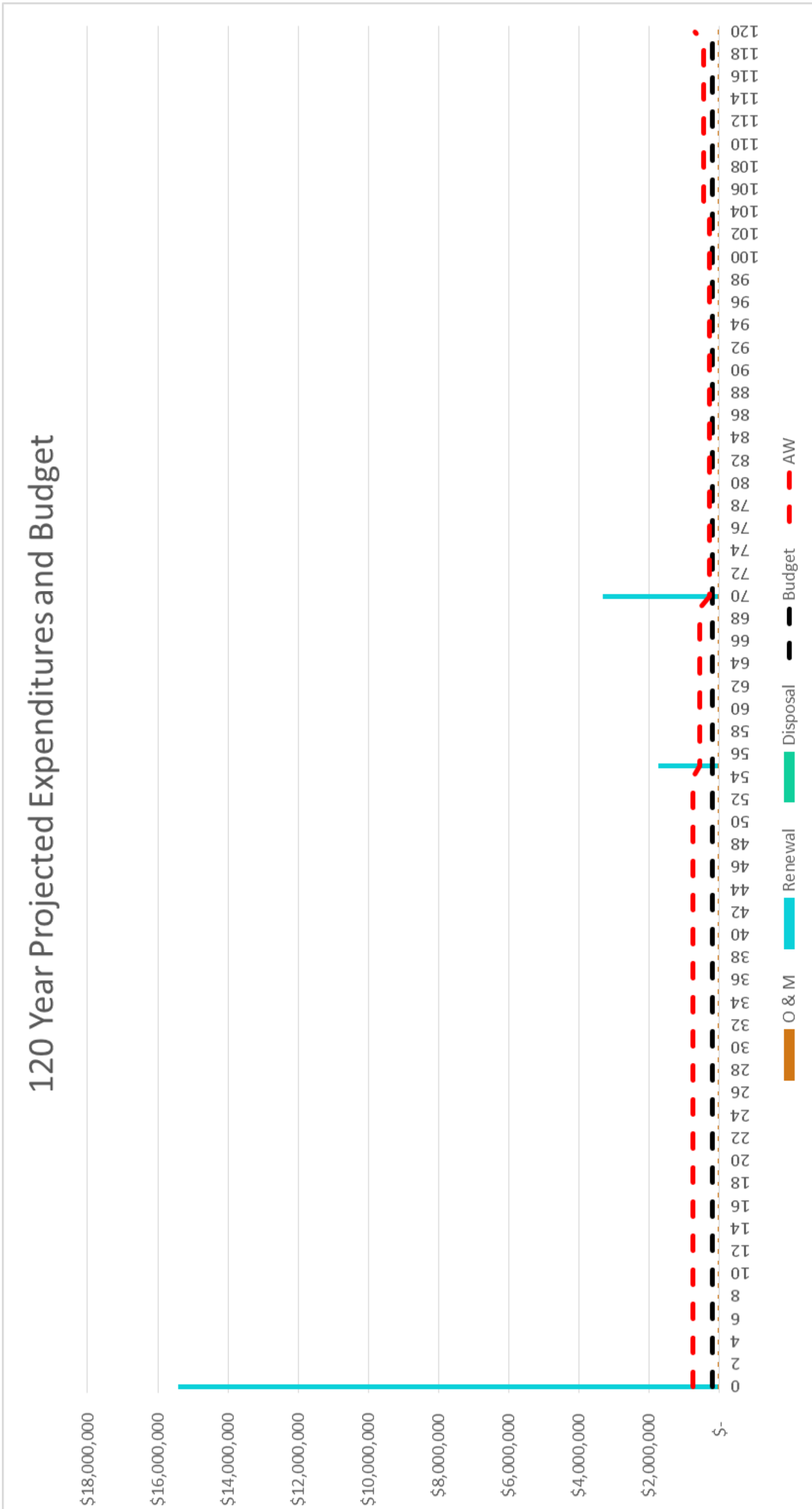


Figure C-3: Town of Shellbrook Existing Network Full Life Cycle Cost Profile – No Uncertainty

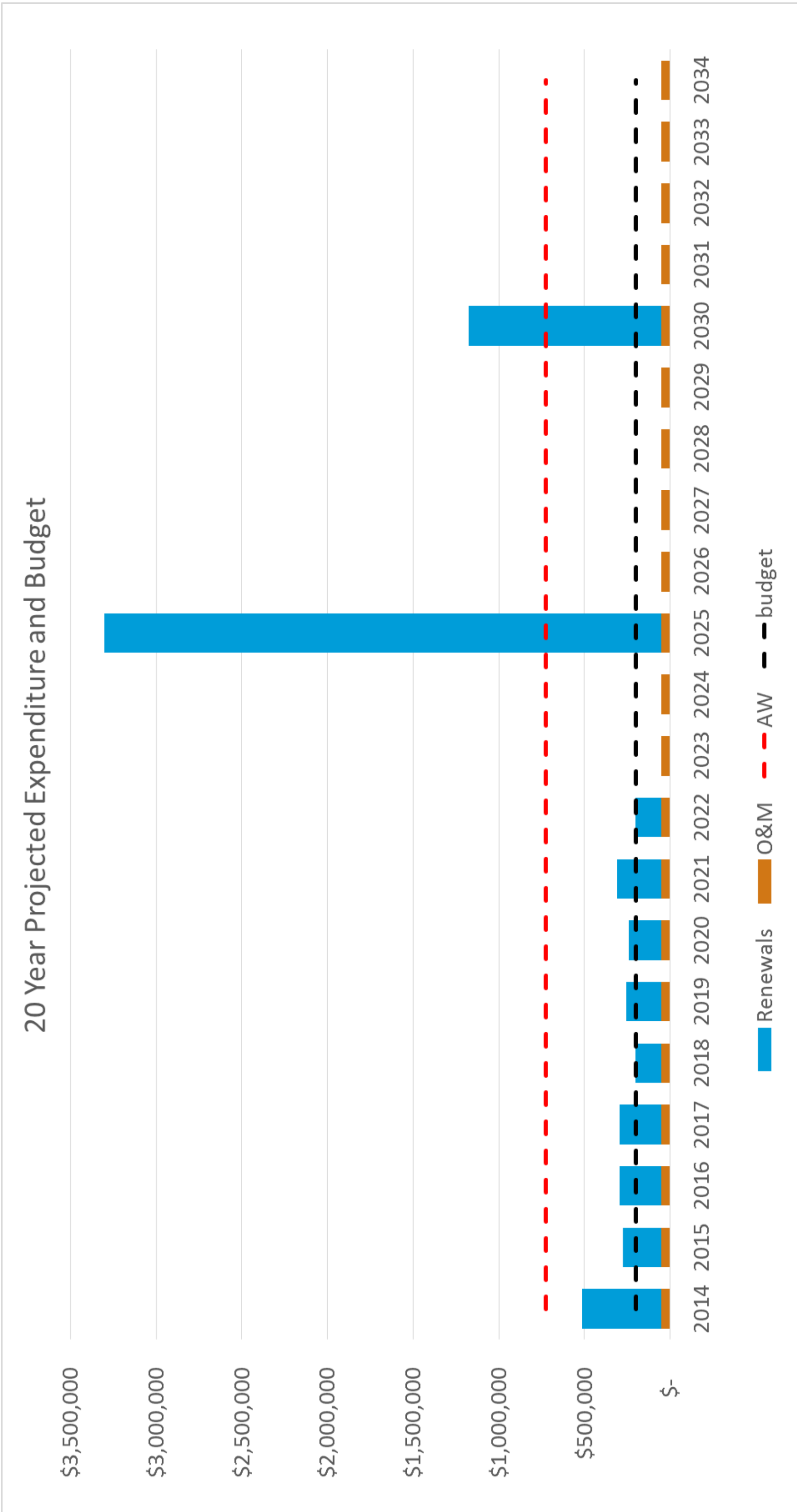
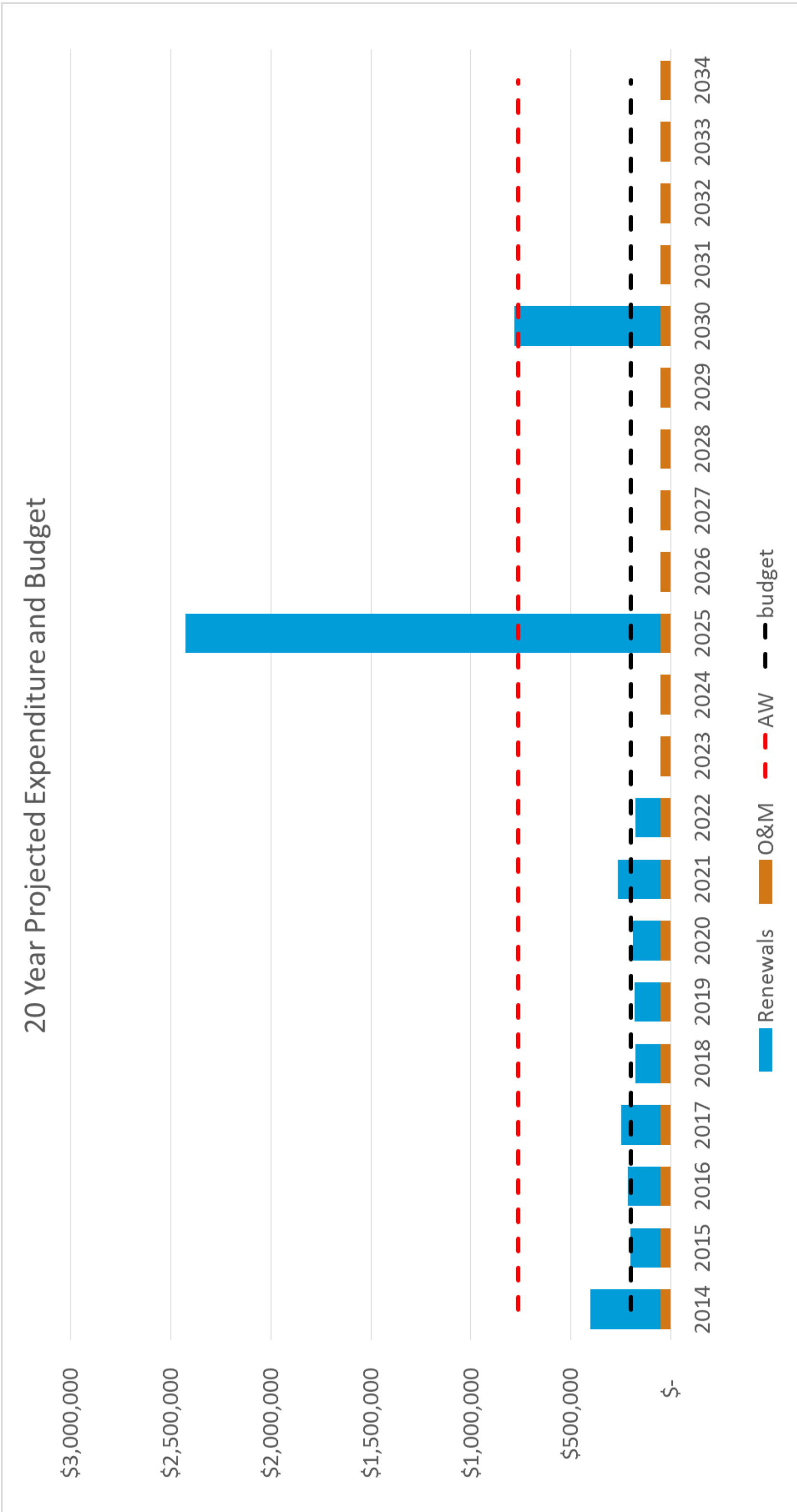


Figure C-4: Town of Shellbrook Existing Network Full Life Cycle Cost Profile – Including Uncertainty at Expected Values



APPENDIX D

RM OF WILTON DATA

Table D-1: RM of Wilton Asset Register

Asset ID	Road Class	Asset Name	Year of Construction	Useful Life	Length	Unit
2379	6	10 A-B	1980	75	0.37	km
610	6	10 B-C	1980	75	0.08	km
623	6	10 B-C	1980	75	0.37	km
1388	6	10 B-C	1980	75	0.01	km
1393	6	10 B-C	1980	75	1.31	km
787	6	10 C-D	1980	75	0.85	km
793	6	10 C-D	1980	75	0.79	km
1889	6	10 D-E	1980	75	1.41	km
1968	6	10 D-E	1980	75	0.23	km
1603	6	10 E-F	1980	75	0.79	km
1905	6	10 E-F	1980	75	0.83	km
890	6	10 F-G	1980	75	1.53	km
1473	6	10 F-G	1980	75	0.10	km
62	6	10 G-H	1960	75	0.83	km
439	6	10 G-H	1960	75	0.81	km
1382	6	10 H-J	1960	75	1.64	km
1596	6	10 J-K	1960	75	1.64	km
2176	6	10 K-L	1960	75	1.63	km
870	5	10 P-Q	1960	65	1.63	km
1548	5	10 Q-R	1960	65	1.63	km
1531	5	10 U-V	1960	65	0.53	km
2073	5	10 U-V	1960	65	1.11	km
2001	5	10 V-W	1960	65	1.64	km
403	5	10 W-X	1960	65	1.61	km
1017	5	10.5 L-M	1960	65	1.64	km
983	5	10.5 M-N	1960	65	0.22	km
998	5	10.5 M-N	1960	65	1.41	km
1582	5	10.5 N-P	1960	65	1.19	km
2075	5	10.5 N-P	1960	65	0.45	km
282	5	10.5 P-Q	1950	65	1.63	km
1422	5	10.5 Q-R	1950	65	1.63	km
162	5	10.5 R-S	1950	65	0.83	km
1810	5	10.5 R-S	1950	65	0.38	km
1842	5	10.5 R-S	1950	65	0.42	km
837	5	10.5 S-T	1950	65	0.33	km
1141	5	10.5 S-T	1950	65	0.89	km
2045	5	10.5 S-T	1950	65	0.57	km
457	6	11 A-B	1950	75	0.24	km

657	6	11 B-C	1950	75	0.29	km
914	6	11 B-C	1950	75	0.16	km
929	6	11 B-C	1950	75	0.62	km
1377	6	11 B-C	1950	75	0.33	km
1606	6	11 B-C	1950	75	0.13	km
2381	6	11 B-C	1950	75	0.24	km
1698	6	11 C-D	1950	75	0.40	km
1699	6	11 C-D	1950	75	1.31	km
496	6	11 T.5-U	1960	75	0.08	km
2048	6	11 T.5-U	1960	75	0.86	km
2383	5	14 A-B	1970	65	0.37	km
18	5	14 B-C	1970	65	0.78	km
644	5	14 B-C	1970	65	0.55	km
671	5	14 B-C	1970	65	0.37	km
1228	5	14 B-C	1970	65	0.08	km
178	5	14 C-D	1970	65	1.19	km
1383	5	14 C-D	1970	65	0.45	km
155	6	14 D-E	1960	75	0.59	km
901	6	14 D-E	1960	75	1.04	km
293	6	14 E-F	1960	75	0.83	km
1456	6	14 E-F	1960	75	0.81	km
267	5	14 H-J	1980	65	1.63	km
746	6	14 N-P	1950	75	1.64	km
490	6	14 P-Q	1950	75	1.64	km
1647	6	14 T-U	1950	75	1.63	km
1368	6	14 U-V	1950	75	1.63	km
1112	6	14 V-W	1950	75	1.63	km
1982	6	14 W-X	1950	75	1.64	km
560	6	16 G-H	1980	75	0.83	km
1208	6	16 G-H	1980	75	0.81	km
944	6	16 H-J	1980	75	0.14	km
981	6	16 H-J	1980	75	1.49	km
412	6	16 J-K	1980	75	0.48	km
1476	6	16 J-K	1980	75	0.81	km
2059	6	16 J-K	1980	75	0.48	km
152	6	16 K-L	1980	75	0.85	km
240	6	16 K-L	1980	75	0.83	km
2203	6	16 K-L	1980	75	0.18	km
2388	6	18 A-B	1950	75	0.38	km
747	6	18 B-C	1950	75	1.37	km
1272	6	18 B-C	1950	75	0.29	km

2003	6	18 B-C	1950	75	0.38	km
1431	6	18 C-D	1950	75	1.39	km
586	6	18 D-E	1950	75	0.50	km
1469	6	18 D-E	1950	75	0.05	km
1944	6	18 D-E	1950	75	0.28	km
2072	6	18 D-E	1950	75	0.79	km
1214	6	18 E-F	1950	75	0.49	km
1236	6	18 E-F	1950	75	0.25	km
1311	6	18 E-F	1950	75	0.89	km
1416	6	18 F-G	1950	75	0.18	km
1460	6	18 F-G	1950	75	1.29	km
1186	4	2 D-E	1970	65	1.19	km
1251	4	2 D-E	1970	65	0.36	km
1886	4	2 D-E	1970	65	0.08	km
2671	4	2 D-E	1970	65	1.19	km
1585	4	2 E-F	1970	65	1.61	km
2139	4	2 E-F	1970	65	0.02	km
979	5	2 F-G	1970	65	1.62	km
264	4	2 L-M	1980	65	1.62	km
1130	4	2 M-N	1980	65	1.40	km
1849	4	2 M-N	1980	65	0.22	km
619	4	2 N-P	1980	65	1.31	km
2242	4	2 N-P	1980	65	2.06	km
40	5	2 P-Q	1970	65	2.06	km
51	6	20 C-D	1960	75	0.81	km
1252	6	20 C-D	1960	75	0.82	km
682	6	20 D-E	1960	75	0.81	km
686	6	20 D-E	1960	75	0.30	km
1011	6	20 D-E	1960	75	0.52	km
1011.1	6	20 E-E.25	1965	75	0.00	km
277	6	20 E-E.5	1960	75	0.72	km
170	6	22 A-B	1970	75	0.30	km
953	6	22 A-B	1970	75	0.38	km
385	6	22 B-C	1970	75	1.63	km
109	6	22 C-D	1970	75	0.82	km
626	6	22 C-D	1970	75	0.81	km
569	6	22 D-E	1970	75	0.39	km
1652	6	22 D-E	1970	75	0.31	km
1846	6	22 D-E	1970	75	0.93	km
386	6	22 E-F	1970	75	0.39	km
838	6	22 E-F	1970	75	0.65	km

1058	6	22 E-F	1970	75	0.81	km
778	6	22 F-G	1970	75	0.17	km
1313	6	22 F-G	1970	75	0.95	km
2158	6	22 F-G	1970	75	0.86	km
2212	6	22 F-G	1970	75	0.03	km
1557	6	24 C-D	1950	75	1.63	km
2246	5	4 A-B	1975	65	0.37	km
147	5	4 B-C	1970	65	1.39	km
799	5	4 B-C	1970	65	0.37	km
1268	5	4 C-D	1970	65	0.77	km
1632	5	4 C-D	1970	65	0.04	km
1635	5	4 C-D	1970	65	0.83	km
1161	5	4 D-E	1970	65	3.26	km
2247	5	4 E-F	1960	65	3.26	km
1376	5	4 F-G	1960	65	1.13	km
1816	5	4 F-G	1960	65	0.50	km
230	4	4 J.75-K	1970	65	0.14	km
66	4	4 K-L	1970	65	1.31	km
873	4	4 K-L	1970	65	0.33	km
525	4	4 L-M	1970	65	1.62	km
426	4	4 M-N	1970	65	1.64	km
399	4	4 N-P	1970	65	1.64	km
951	4	4 P-Q	1970	65	1.63	km
483	4	4 Q-R	1970	65	1.63	km
330	4	4 R-S	1970	65	1.63	km
1027	4	4 S-T	1970	65	1.63	km
2128	4	4 T-U	1970	65	1.63	km
1363	4	4 U-V	1970	65	1.63	km
1155	5	4 V-W	1970	65	0.81	km
1811	5	4 V-W	1970	65	0.82	km
14	5	4 W-X	1975	65	0.80	km
1695	5	4 W-X	1975	65	0.81	km
2377	5	8 A-B	1970	65	0.37	km
683	5	8 B-C	1970	65	0.98	km
939	5	8 B-C	1970	65	0.42	km
1398	5	8 B-C	1970	65	0.37	km
1097	4	8 C-D	1970	65	0.80	km
1118	4	8 C-D	1970	65	0.13	km
1899	4	8 C-D	1970	65	0.71	km
1703	6	8 D-E	1960	75	1.63	km
57	6	8 E-F	1960	75	0.28	km

78	6	8 E-F	1960	75	0.02	km
467	6	8 E-F	1960	75	0.52	km
1567	6	8 E-F	1960	75	0.34	km
1618	6	8 E-F	1960	75	0.01	km
2027	6	8 E-F	1960	75	0.45	km
2027.1	4	8 J.5-K	1960	65	0.00	km
506	4	8 L-M	2000	65	1.64	km
2138	4	8 M-N	2000	65	1.63	km
291	6	8 R-S	1970	75	0.33	km
952	6	8 R-S	1970	75	0.02	km
969	6	8 R-S	1970	75	0.80	km
1530	6	8 R-S	1970	75	0.48	km
1379	6	8 S-T	1970	75	0.10	km
1385	6	8 S-T	1970	75	0.02	km
1392	6	8 S-T	1970	75	0.81	km
1626	6	8 S-T	1970	75	0.71	km
73	5	8 T-U	2000	65	0.33	km
594	5	8 T-U	2000	65	0.32	km
967	5	8 T-U	2000	65	0.49	km
1765	5	8 T-U	2000	65	0.25	km
2169	5	8 T-U	2000	65	0.25	km
2041	5	8 U-V	2000	65	1.62	km
1740	5	8 V-W	2000	65	1.64	km
1334	5	8 W-X	2000	65	1.61	km
94	5	A 16-17	1960	65	1.93	km
1181	5	A 16-17	1960	65	0.00	km
276	5	B 21-22	1960	65	1.53	km
743	5	B 21-22	1960	65	0.09	km
63	5	B 22-23	1960	65	1.67	km
63.1	6	B 25.5-26	1965	75	0.00	km
1239	6	C 15.5-16	1960	75	0.21	km
1985	6	C 15.5-16	1960	75	0.60	km
908	5	C 16-17	1980	65	0.72	km
2395	5	C 16-17	1980	65	2.58	km
266	5	C 17-18	1980	65	2.58	km
1746	5	C 18-19	1980	65	1.89	km
272	5	C 19-20	1980	65	1.42	km
2396	5	C 19-20	1980	65	1.89	km
1839	5	C 20-21	1980	65	0.82	km
2397	5	C 20-21	1980	65	2.43	km
1832	5	C 21-22	1980	65	2.43	km

669	5	C 22-23	1980	65	3.25	km
2398	5	C 23-24	1980	65	3.25	km
1508	6	C 4-4.5	1950	75	0.78	km
571	6	C 6-7	1950	75	0.48	km
2393	6	C 6-7	1950	75	2.29	km
773	6	C 8-9	1960	75	0.30	km
986	6	C 8-9	1960	75	0.51	km
1454	6	C 8-9	1960	75	0.81	km
1247	6	C 9-10	1960	75	0.30	km
1662	6	C 9-10	1960	75	0.51	km
1792	6	C 9-10	1960	75	0.78	km
1783	5	D 10-11	1970	65	1.62	km
142	5	D 11-12	1970	65	0.16	km
885	5	D 11-12	1970	65	1.47	km
56	5	D 12-13	1980	65	0.28	km
1068	5	D 12-13	1980	65	0.05	km
1625	5	D 12-13	1980	65	0.48	km
1829	5	D 12-13	1980	65	0.82	km
1858	5	D 13-14	1980	65	0.15	km
1914	5	D 13-14	1980	65	0.37	km
2086	5	D 13-14	1980	65	1.09	km
1192	5	D 14-15	1980	65	0.37	km
1452	5	D 14-15	1980	65	0.62	km
1646	5	D 14-15	1980	65	0.82	km
494	5	D 15-16	1980	65	0.81	km
1558	5	D 15-16	1980	65	0.51	km
2155	5	D 15-16	1980	65	0.12	km
2405	5	D 15-16	1980	65	0.37	km
798	6	D 16-17	1960	75	1.83	km
558	6	D 17-18	1960	75	0.61	km
1569	6	D 17-18	1960	75	0.78	km
2406	6	D 17-18	1960	75	1.83	km
65	6	D 18-19	1960	75	0.02	km
848	6	D 18-19	1960	75	0.74	km
1073	6	D 18-19	1960	75	0.53	km
1553	6	D 18-19	1960	75	0.31	km
3	6	D 19-20	1960	75	0.43	km
313	6	D 19-20	1960	75	0.60	km
1417	6	D 19-20	1960	75	0.37	km
1795	6	D 19-20	1960	75	0.21	km
1322	6	D 20-21	1960	75	1.08	km

2407	6	D 20-21	1960	75	1.34	km
867	6	D 21-22	1960	75	0.83	km
2097	6	D 21-22	1960	75	1.34	km
706	6	D 22-23	1960	75	0.31	km
2408	6	D 22-23	1960	75	2.99	km
1041	5	D 2-3	1970	65	0.15	km
1427	5	D 2-3	1970	65	0.60	km
2403	5	D 2-3	1970	65	2.49	km
817	6	D 23-24	1960	75	2.99	km
841	6	D 24-25	1960	75	1.07	km
1143	6	D 24-25	1960	75	0.64	km
1992	5	D 3-4	1970	65	2.49	km
655	5	D 4-5	1970	65	0.26	km
1718	5	D 4-5	1970	65	0.87	km
2236	5	D 4-5	1970	65	0.51	km
1522	5	D 5-6	1970	65	1.22	km
2129	5	D 5-6	1970	65	0.39	km
387	5	D 6-7	1970	65	0.14	km
591	5	D 6-7	1970	65	0.17	km
1453	5	D 6-7	1970	65	0.37	km
1631	5	D 6-7	1970	65	0.20	km
2112	5	D 6-7	1970	65	0.70	km
2404	5	D 6-7	1970	65	0.29	km
590	5	D 7-8	1970	65	0.27	km
723	5	D 7-8	1970	65	0.16	km
1018	5	D 7-8	1970	65	0.59	km
1106	5	D 7-8	1970	65	0.22	km
1160	5	D 7-8	1970	65	0.13	km
1825	5	D 7-8	1970	65	0.29	km
120	5	D 8-9	1970	65	0.31	km
681	5	D 8-9	1970	65	0.29	km
1275	5	D 8-9	1970	65	0.50	km
2028	5	D 8-9	1970	65	0.04	km
2180	5	D 8-9	1970	65	0.49	km
829	5	D 9-10	1970	65	1.62	km
674	5	E 0-.5	1970	65	0.93	km
2409	5	E .5-1	1970	65	1.68	km
1713	4	E 10.5-11	1980	65	0.81	km
2120	5	E 1-2	1970	65	1.68	km
2147	5	E 1-2	1970	65	0.56	km
643	6	E 14-15	1960	75	0.57	km

713	6	E 14-15	1960	75	0.37	km
2182	6	E 14-15	1960	75	0.68	km
895	6	E 15-16	1960	75	0.54	km
1096	6	E 15-16	1960	75	0.23	km
1607	6	E 15-16	1960	75	0.85	km
2412	6	E 15-16	1960	75	0.85	km
38	5	E 16-17	1960	65	0.71	km
684	5	E 16-17	1960	65	0.81	km
701	5	E 16-17	1960	65	0.10	km
90	5	E 17-18	1960	65	0.55	km
392	5	E 17-18	1960	65	0.79	km
1435	5	E 17-18	1960	65	0.25	km
304	6	E 18-19	1990	75	0.66	km
730	6	E 18-19	1990	75	2.31	km
2413	6	E 19-19.5	1990	75	2.31	km
446	4	E 22-23	1970	65	1.61	km
294	4	E 23-24	1970	65	0.26	km
480	4	E 23-24	1970	65	0.77	km
1689	4	E 23-24	1970	65	0.04	km
641	5	F .75 -1	1970	65	0.02	km
2119	5	F .75 -1	1970	65	0.61	km
868	5	F 10-11	1960	65	0.30	km
1786	5	F 10-11	1960	65	0.57	km
1821	5	F 10-11	1960	65	0.53	km
2234	5	F 10-11	1960	65	0.23	km
373	5	F 11-11.5	1960	65	1.61	km
531	5	F 1-2	1970	65	0.40	km
595	5	F 1-2	1970	65	0.06	km
651	5	F 1-2	1970	65	0.10	km
666	5	F 1-2	1970	65	0.13	km
791	5	F 1-2	1970	65	0.53	km
2009	5	F 1-2	1970	65	0.09	km
1378	6	F 12-13	2000	75	0.80	km
1621	6	F 12-13	2000	75	0.81	km
296	6	F 13-14	2000	75	0.91	km
1005	6	F 13-14	2000	75	0.41	km
1193	6	F 13-14	2000	75	0.31	km
443	4	F 22.5-23	1990	65	0.58	km
2418	4	F 22.5-23	1990	65	0.95	km
1864	5	F 2-3	1970	65	0.10	km
1997	5	F 2-3	1970	65	1.50	km

184	5	F 3-4	1970	65	0.82	km
2172	5	F 3-4	1970	65	0.83	km
461	5	F 4-5	1980	65	1.54	km
2414	5	F 4-5	1980	65	0.15	km
10	5	F 5-6	1980	65	0.22	km
174	5	F 5-6	1980	65	0.67	km
422	5	F 5-6	1980	65	0.40	km
1439	5	F 5-6	1980	65	0.25	km
2109	5	F 5-6	1980	65	0.15	km
274	5	F 6-7	1970	65	0.71	km
2235	5	F 6-7	1970	65	0.91	km
1615	5	F 7-8	1970	65	1.62	km
1615.1	5	F 8-9	1975	65	0.00	km
1856	6	G 0-1	1970	75	1.59	km
493	6	G 1-2	1970	75	0.13	km
613	6	G 1-2	1970	75	0.28	km
614	6	G 1-2	1970	75	0.60	km
1244	6	G 1-2	1970	75	0.11	km
1938	6	G 1-2	1970	75	0.03	km
2005	6	G 1-2	1970	75	0.05	km
2166	6	G 1-2	1970	75	0.38	km
529	6	G 18-19	1980	75	0.32	km
1373	6	G 18-19	1980	75	0.78	km
2190	6	G 18-19	1980	75	0.49	km
1094	5	G 2-3	1990	65	1.63	km
726	5	G 3-4	1990	65	1.05	km
805	5	G 3-4	1990	65	0.25	km
2192	5	G 3-4	1990	65	0.31	km
1067	5	Grid	1970	65	1.52	km
1878	5	H 10-11	1980	65	1.84	km
99	6	H 12-13	1970	75	1.10	km
1364	6	H 12-13	1970	75	0.81	km
2187	6	H 12-13	1970	75	0.01	km
1045	6	H 13-14	1970	75	1.32	km
2431	6	H 13-14	1970	75	1.10	km
2006	5	H 14-15	1970	65	1.50	km
2432	5	H 14-15	1970	65	0.42	km
87	5	H 15-16	1970	65	0.44	km
258	5	H 15-16	1970	65	0.33	km
1129	5	H 15-16	1970	65	0.51	km
1474	5	H 15-16	1970	65	0.05	km

1648	5	H 15-16	1970	65	0.42	km
500	5	H 16-17	1970	65	0.46	km
1415	5	H 16-17	1970	65	0.02	km
1491	5	H 16-17	1970	65	0.34	km
2052	5	H 16-17	1970	65	0.90	km
414	5	H 17-18	1970	65	1.09	km
1009	5	H 17-18	1970	65	0.39	km
2433	5	H 17-18	1970	65	0.90	km
121	5	H 18-19	2000	65	0.22	km
855	5	H 18-19	2000	65	0.03	km
1502	5	H 18-19	2000	65	0.31	km
1681	5	H 18-19	2000	65	0.38	km
2113	5	H 18-19	2000	65	0.37	km
2375	5	H 18-19	2000	65	0.79	km
2434	5	H 19-19.5	2000	65	0.97	km
285	6	H 2-2.5	1990	75	0.74	km
1412	5	H 5-6	2000	65	0.80	km
1527	5	H 5-6	2000	65	0.80	km
2100	5	H 6-7	1960	65	1.52	km
2428	5	H 6-7	1960	65	0.44	km
1063	6	J 0-1	1970	75	0.68	km
2465	6	J 0-1	1970	75	2.39	km
297	6	J 1-2	1970	75	2.39	km
922	6	J 1-2	1970	75	0.12	km
1494	6	J 15-16	1960	75	1.68	km
584	5	J 2-3	1970	65	2.14	km
790	5	J 3.4-4	1970	65	1.03	km
1526	5	J 3.4-4	1970	65	0.04	km
2466	5	J 3-3.4	1970	65	2.14	km
302	5	J 4-5	1980	65	1.21	km
1436	5	J 4-5	1980	65	0.40	km
550	5	J 5-6	1980	65	0.80	km
741	5	J 5-6	1980	65	0.30	km
1493	5	J 5-6	1980	65	0.52	km
227	6	J 6-7	1950	75	1.62	km
769	6	J 6-7	1950	75	0.30	km
1907	6	J 6-7	1950	75	0.50	km
1544	6	J 7-8	1950	75	0.33	km
2467	6	J 7-8	1950	75	1.62	km
2468	6	J 7-8	1950	75	1.29	km
1935	6	J 8-9	1950	75	1.29	km

2469	6	J 8-9	1950	75	2.43	km
1308	6	J 9-10	1950	75	2.43	km
1624	6	J.5 16-17	1960	75	1.62	km
537	6	J.5 17-18	1960	75	0.82	km
835	6	J.5 17-18	1960	75	0.71	km
869	6	J.5 17-18	1960	75	0.09	km
2477	6	K 10-11	1960	75	3.24	km
1115	6	K 11-12	1960	75	3.24	km
904	5	K 1-2	1970	65	1.03	km
1780	5	K 1-2	1970	65	1.08	km
2474	5	K 1-2	1970	65	1.03	km
2474.1	6	K 5.5-6	1975	75	0.00	km
1410	5	K 2-3	1960	65	0.02	km
1627	5	K 2-3	1960	65	0.81	km
2476	5	K 2-3	1960	65	2.42	km
1801	5	K 3-4	1960	65	2.42	km
853	5	L 0-1	1980	65	2.81	km
541	4	L 10-11	1980	65	0.20	km
1576	4	L 10-11	1980	65	0.81	km
2046	4	L 10-11	1980	65	0.78	km
499	4	L 11-12	1980	65	0.57	km
1505	4	L 11-12	1980	65	0.88	km
2486	4	L 11-12	1980	65	0.78	km
926	5	L 1-2	1980	65	0.12	km
1298	6	L 1-2	1970	75	0.12	km
1659	5	L 1-2	1980	65	0.27	km
2481	5	L 1-2	1980	65	2.81	km
660	4	L 12-13	1980	65	0.78	km
956	4	L 12-13	1980	65	0.51	km
2241	4	L 12-13	1980	65	1.95	km
1913	5	L 13-14	1980	65	1.95	km
34	5	L 14-15	1980	65	0.49	km
433	5	L 14-15	1980	65	0.44	km
501	5	L 14-15	1980	65	0.69	km
354	5	L 15-16	1990	65	0.82	km
1925	5	L 15-16	1990	65	0.80	km
1593	5	L 16-17	1990	65	3.20	km
2488	5	L 17-18	1990	65	3.20	km
999	5	L 2-3	1980	65	0.83	km
1750	5	L 2-3	1980	65	0.81	km
819	5	L 3-4	1980	65	0.79	km

1285	5	L 3-4	1980	65	0.82	km
2483	4	L 6.5-7	1980	65	2.53	km
672	4	L 7-8	1980	65	2.53	km
2485	4	L 8-9	1980	65	1.74	km
231	4	L 9-10	1980	65	0.16	km
382	4	L 9-10	1980	65	0.31	km
600	4	L 9-10	1980	65	0.25	km
2140	4	L 9-10	1980	65	1.74	km
2489	6	M .5-2	1970	75	1.90	km
861	5	M 11.5-12	1960	65	0.54	km
744	6	M 1-2	1970	75	1.90	km
2494	5	M 12-13	1960	65	3.25	km
825	5	M 13-14	1960	65	3.25	km
271	5	M 14-15	1960	65	1.11	km
1040	5	M 14-15	1960	65	0.51	km
828	5	M 15-16	1960	65	0.49	km
915	5	M 15-16	1960	65	0.10	km
1194	5	M 15-16	1960	65	0.73	km
2094	5	M 15-16	1960	65	0.31	km
341	5	M 16-17	1960	65	1.80	km
305	6	M 2-3	1970	75	0.82	km
625	6	M 2-3	1970	75	1.60	km
1571	5	M 3-4	1970	65	0.82	km
2490	5	M 3-4	1970	65	1.60	km
782	6	M 4-5	1970	75	3.24	km
2491	6	M 5-6	1970	75	3.24	km
1612	5	M 6.5-7	1980	65	0.04	km
2492	5	M 6.5-7	1980	65	1.33	km
2492.1	5	Mitchell Road 1	1985	65	0.00	km
2492.2	5	Mitchell Road 2	1975	65	0.00	km
2492.3	5	Mitchell Road 3	1975	65	0.00	km
323	5	N 1-2	1960	65	0.12	km
561	5	N 1-2	1960	65	1.06	km
324	6	N 12-13	1960	75	0.81	km
689	6	N 12-13	1960	75	0.57	km
2087	6	N 12-13	1960	75	0.23	km
381	6	N 13-14	2000	75	0.80	km
2065	6	N 13-14	2000	75	0.82	km
711	5	N 2-3	1960	65	3.25	km
2495	5	N 3-4	1960	65	3.25	km
2038	5	N 4-5	1960	65	3.23	km

2496	5	N 5-6	1960	65	3.23	km
466	5	N 6-7	1960	65	1.35	km
2497	5	N 6-7	1960	65	0.67	km
1050	5	N 7-7.25	1960	65	0.67	km
1166	5	N 7-7.25	1960	65	0.15	km
1424	5	P 0-1	1980	65	1.56	km
1187	5	P 10-11	1950	65	0.81	km
2503	5	P 10-11	1950	65	2.44	km
1969	5	P 11-12	1950	65	2.44	km
1400	5	P 12-13	1990	65	1.23	km
1911	5	P 12-13	1990	65	0.74	km
35	5	P 13-14	1990	65	0.17	km
1188	5	P 13-14	1990	65	0.92	km
1203	5	P 13-14	1990	65	0.19	km
2504	5	P 13-14	1990	65	0.74	km
1815	5	P 14-15	1990	65	1.93	km
2500	6	P 2.5-3	1950	75	2.77	km
1578	6	P 3-4	1950	75	2.77	km
216	6	P 4-4.5	1950	75	0.91	km
454	6	P 5.5-6	1950	75	1.00	km
1144	5	P 6-7	1950	65	2.66	km
822	5	P 7-8	1950	65	0.05	km
1533	5	P 7-8	1950	65	0.43	km
1940	5	P 7-8	1950	65	0.31	km
2501	5	P 7-8	1950	65	2.66	km
813	5	P 8-9	1950	65	0.04	km
1292	5	P 8-9	1950	65	0.19	km
1542	5	P 8-9	1950	65	0.12	km
2502	5	P 8-9	1950	65	2.93	km
377	5	P 9-10	1950	65	2.93	km
36	5	Q 10-11	1970	65	0.27	km
1366	5	Q 10-11	1970	65	0.54	km
2512	5	Q 10-11	1970	65	2.16	km
568	5	Q 11-12	1970	65	2.16	km
2063	5	Q 11-12	1970	65	0.28	km
1834	5	Q 12-13	1970	65	1.60	km
119	5	Q 13-14	1970	65	0.32	km
705	5	Q 13-14	1970	65	0.11	km
1116	5	Q 13-14	1970	65	0.28	km
1240	5	Q 13-14	1970	65	0.25	km
1981	5	Q 13-14	1970	65	0.16	km

2081	5	Q 13-14	1970	65	0.51	km
238	5	Q 14-15	1970	65	0.34	km
290	5	Q 14-15	1970	65	0.71	km
1052	5	Q 14-15	1970	65	0.67	km
292	5	Q 15-16	1970	65	0.66	km
363	5	Q 15-16	1970	65	0.24	km
1784	5	Q 15-16	1970	65	0.37	km
1978	5	Q 15-16	1970	65	0.25	km
2513	5	Q 15-16	1970	65	0.67	km
420	6	Q 5-6	1990	75	1.47	km
2508	6	Q 5-6	1990	75	1.77	km
160	5	Q 7-8	1990	65	0.28	km
268	5	Q 7-8	1990	65	0.24	km
491	5	Q 7-8	1990	65	0.06	km
2193	5	Q 7-8	1990	65	0.18	km
2509	5	Q 7-8	1990	65	1.92	km
2510	5	Q 7-8	1990	65	1.36	km
113	5	Q 8-9	1990	65	0.18	km
732	5	Q 8-9	1990	65	0.05	km
1667	5	Q 8-9	1990	65	1.36	km
2197	5	Q 8-9	1990	65	0.59	km
2511	5	Q 8-9	1990	65	1.68	km
1568	5	Q 9-10	1970	65	1.68	km
321	5	R 0-1	1980	65	1.62	km
442	5	R 1.75-2	1980	65	0.12	km
664	5	R 1.75-2	1980	65	0.28	km
1211	6	R 10-11	1970	75	0.81	km
2517	6	R 10-11	1970	75	2.43	km
154	5	R 11-12	1980	65	2.43	km
1395	5	R 12-13	1980	65	1.61	km
12	5	R 13-14	1980	65	0.43	km
796	5	R 13-14	1980	65	0.35	km
878	5	R 13-14	1980	65	0.04	km
1202	5	R 13-14	1980	65	0.29	km
1872	5	R 13-14	1980	65	0.52	km
1761	6	R 14-15	2000	75	0.27	km
1819	6	R 14-15	2000	75	0.32	km
1993	6	R 14-15	2000	75	0.50	km
2518	6	R 14-15	2000	75	1.38	km
720	6	R 15-16	2000	75	1.38	km
348	5	R 2-3	1980	65	1.61	km

1060	5	R 3-4	1980	65	1.63	km
42	6	R 4-5	1980	75	3.19	km
1532	6	R 5-6	1980	75	0.05	km
2515	6	R 5-6	1980	75	3.19	km
897	6	R 6-7	1980	75	1.62	km
925	6	R 6-7	1980	75	0.80	km
48	6	R 7-8	1980	75	0.82	km
2516	6	R 7-8	1980	75	1.62	km
358	5	R 9-10	1970	65	0.05	km
374	5	R 9-10	1970	65	1.10	km
1340	5	R 9-10	1970	65	0.43	km
207	5	S 12-13	1990	65	0.32	km
1305	5	S 12-13	1990	65	0.58	km
1896	5	S 12-13	1990	65	0.49	km
2239	5	S 12-13	1990	65	0.49	km
2519	6	S 2.5-3	1960	75	2.49	km
310	6	S 3-4	1960	75	2.49	km
555	6	S 6-7	1990	75	0.61	km
910	6	S 6-7	1990	75	1.24	km
133	6	S 7-8	1990	75	0.39	km
462	6	S 7-8	1990	75	0.15	km
1477	6	S 7-8	1990	75	0.15	km
1538	6	S 7-8	1990	75	0.41	km
1787	6	S 7-8	1990	75	0.28	km
2521	6	S 7-8	1990	75	1.24	km
219	5	S 8-9	1990	65	0.53	km
1418	5	S 8-9	1990	65	0.51	km
1419	5	S 8-9	1990	65	0.24	km
2171	5	S 8-9	1990	65	0.34	km
1511	5	S 9-10	1990	65	1.59	km
1692	5	S 9-10	1990	65	0.01	km
1643	5	T 0-1	1970	65	1.62	km
812	5	T 12-13	1970	65	1.54	km
1704	5	T 12-13	1970	65	0.39	km
2177	5	T 13-14	1970	65	1.32	km
2525	5	T 13-14	1970	65	1.54	km
797	5	T 14-15	1970	65	0.84	km
988	5	T 14-15	1970	65	0.79	km
1803	5	T 15-16	1970	65	0.48	km
2232	5	T 15-16	1970	65	0.56	km
193	6	U 0-1	1980	75	1.37	km

1791	6	U 0-1	1980	75	0.31	km
70	6	U 11-11.5	1990	75	0.71	km
1262	5	U 2-3	1980	65	0.30	km
2526	5	U 2-3	1980	65	2.34	km
370	5	U 3-4	1980	65	2.34	km
45	5	V 10-11	1990	65	0.56	km
201	5	V 10-11	1990	65	0.80	km
709	5	V 10-11	1990	65	0.25	km
997	5	V 11-12	1990	65	2.19	km
104	5	V 12-13	1980	65	1.98	km
843	5	V 12-13	1980	65	0.64	km
559	5	V 13-14	1980	65	1.19	km
2530	5	V 13-14	1980	65	1.98	km
182	5	V 14-15	1980	65	0.22	km
2130	5	V 14-15	1980	65	0.81	km
2134	5	V 14-15	1980	65	0.60	km
1768	5	V 15-15.5	1980	65	0.31	km
2372	5	V 15-15.5	1980	65	1.52	km
1407	6	V 4-5	1970	75	1.65	km
1614	6	V 5-6	1970	75	0.83	km
2111	6	V 5-6	1970	75	0.77	km
2529	6	V 5-6	1970	75	1.65	km
883	6	V 7.5-8	1980	75	0.24	km
1132	6	V 7.5-8	1980	75	0.59	km
1321	6	V 7.5-8	1980	75	0.17	km
821	6	V 8-9	1980	75	0.78	km
975	6	V 8-9	1980	75	0.51	km
1584	6	V 8-9	1980	75	0.02	km
1917	6	V 8-9	1980	75	0.30	km
2535	5	W 12-13	1960	65	3.20	km
1725	5	W 13-14	1960	65	3.20	km
2532	5	W 2.5-3	1980	65	2.60	km
185	5	W 3-4	1980	65	2.60	km
1922	5	W 3-4	1980	65	0.52	km

Table D-2: RM of Wilton Operation and Maintenance Activities

	Unit	Total Unit Cost ($/yr)	Total O & M ($/yr)
Road Class 4			***$ 12,090***
Grading - 4	per km/yr	$ 6,960	
Regravelling - 4	per km/yr	$ 2,800	
Dust Control - 4	per km/yr	$ 1,830	
Shoulder Pulling - 4	per km/yr	$ 500	
Road Class 5			***$ 8,470***
Grading - 5	per km/yr	$ 5,220	
Regravelling - 5	per km/yr	$ 1,370	
Dust Control - 5	per km/yr	$ 1,830	
Shoulder Pulling - 5	per km/yr	$ 50	
Road Class 6			***$ 5,990***
Grading - 6	per km/yr	$ 3,480	
Regravelling - 6	per km/yr	$ 820	
Dust Control - 6	per km/yr	$ 1,660	
Shoulder Pulling - 6	per km/yr	$ 30	

Table D-3: RM of Wilton Gravel Index

Year	At No Gravel Cost Increase	At 2% Gravel Cost Increase	At 7% Gravel Cost Increase	At 10% Gravel Cost Increase
0	100%	100%	100%	100%
1	100%	102%	107%	110%
2	100%	104%	114%	121%
3	100%	106%	123%	133%
4	100%	108%	131%	146%
5	100%	110%	140%	161%
6	100%	113%	150%	177%
7	100%	115%	161%	195%
8	100%	117%	172%	214%
9	100%	120%	184%	236%
10	100%	122%	197%	259%
11	100%	124%	210%	285%
12	100%	127%	225%	300%
13	100%	129%	241%	300%
14	100%	132%	258%	300%
15	100%	135%	276%	300%
16	100%	137%	295%	300%
17	100%	140%	300%	300%
18	100%	143%	300%	300%
19	100%	146%	300%	300%
20	100%	149%	300%	300%
21	100%	152%	300%	300%
22	100%	155%	300%	300%
23	100%	158%	300%	300%
24	100%	161%	300%	300%
25	100%	164%	300%	300%
26	100%	167%	300%	300%
27	100%	171%	300%	300%
28	100%	174%	300%	300%
29	100%	178%	300%	300%
30	100%	181%	300%	300%
31	100%	185%	300%	300%
32	100%	188%	300%	300%
33	100%	192%	300%	300%
34	100%	196%	300%	300%
35	100%	200%	300%	300%
36	100%	204%	300%	300%
37	100%	208%	300%	300%

38	100%	212%	300%	300%
39	100%	216%	300%	300%
40	100%	221%	300%	300%
41	100%	225%	300%	300%
42	100%	230%	300%	300%
43	100%	234%	300%	300%
44	100%	239%	300%	300%
45	100%	244%	300%	300%
46	100%	249%	300%	300%
47	100%	254%	300%	300%
48	100%	259%	300%	300%
49	100%	264%	300%	300%
50	100%	269%	300%	300%
51	100%	275%	300%	300%
52	100%	280%	300%	300%
53	100%	286%	300%	300%
54	100%	291%	300%	300%
55	100%	297%	300%	300%
56	100%	300%	300%	300%
57	100%	300%	300%	300%
58	100%	300%	300%	300%
59	100%	300%	300%	300%
60	100%	300%	300%	300%
61	100%	300%	300%	300%
62	100%	300%	300%	300%
63	100%	300%	300%	300%
64	100%	300%	300%	300%
65	100%	300%	300%	300%
66	100%	300%	300%	300%
67	100%	300%	300%	300%
68	100%	300%	300%	300%
69	100%	300%	300%	300%
70	100%	300%	300%	300%

Figure D-1: RM of Wilton Proposed Network Full Life Cycle Cost Profile – No Uncertainty

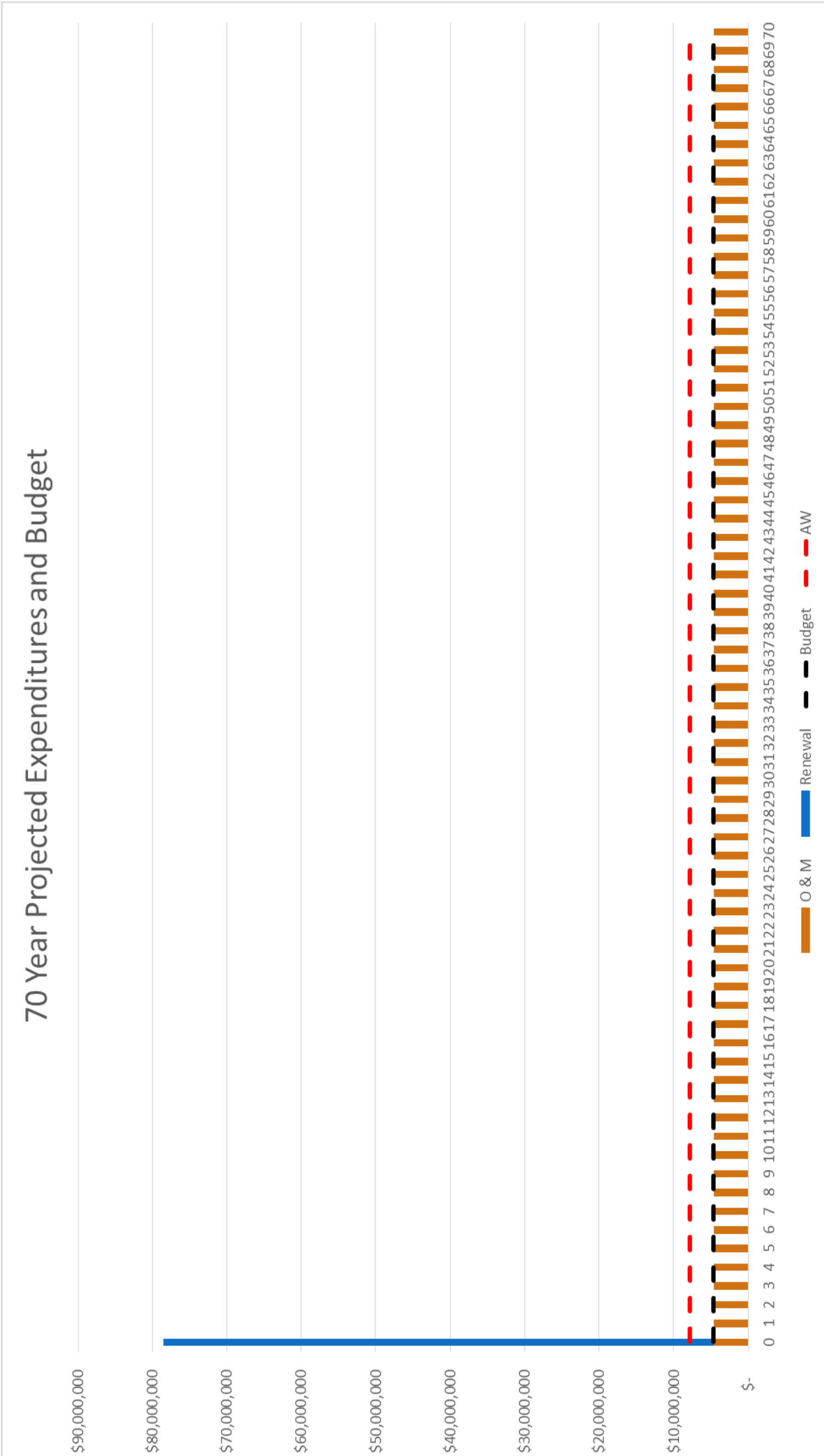


Figure D-2: RM of Wilton Proposed Network Full Life Cycle Cost Profile – Including Uncertainty at Expected Values

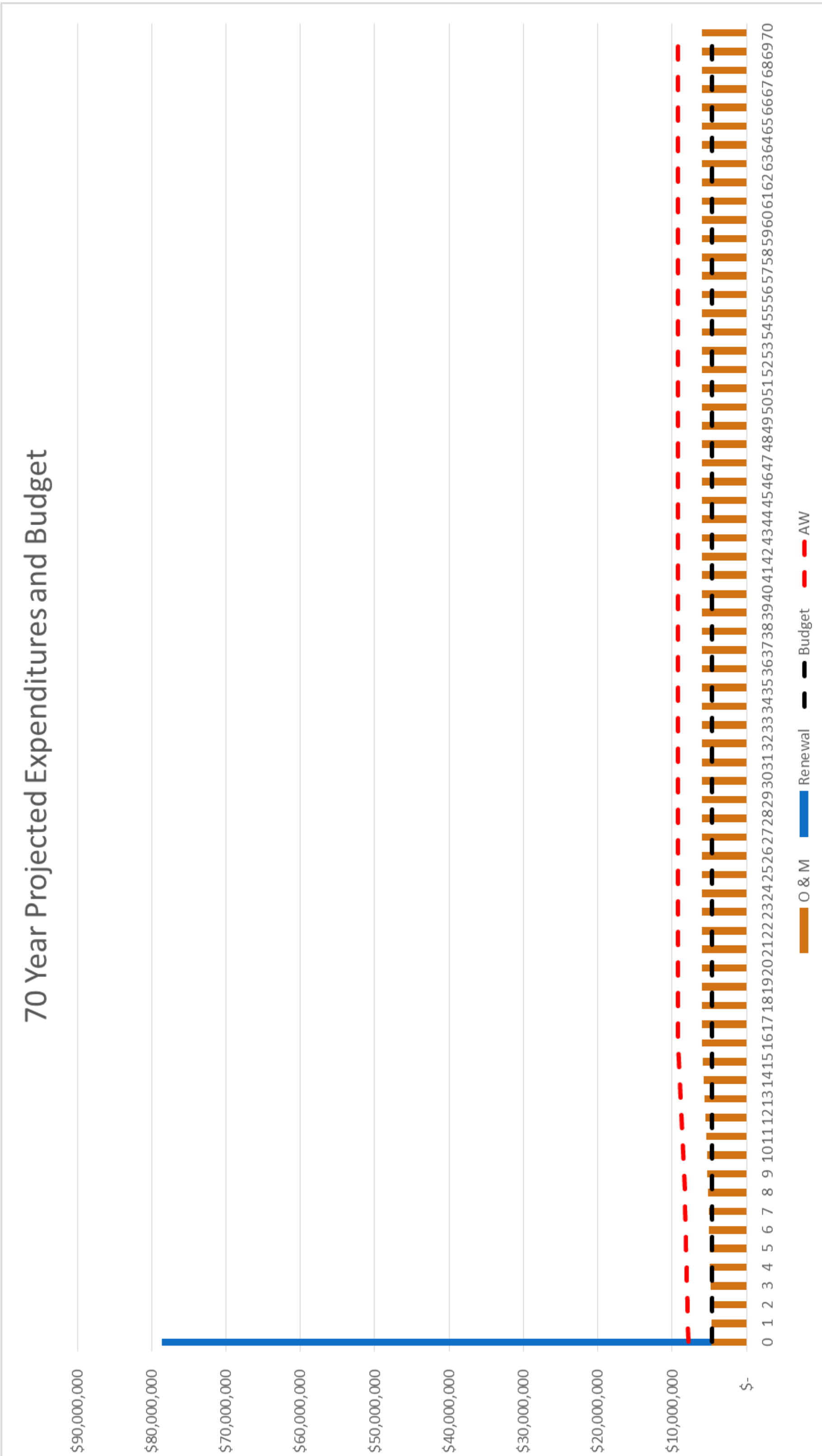


Figure D-3: RM of Wilton Existing Network Full Life Cycle Cost Profile – No Uncertainty

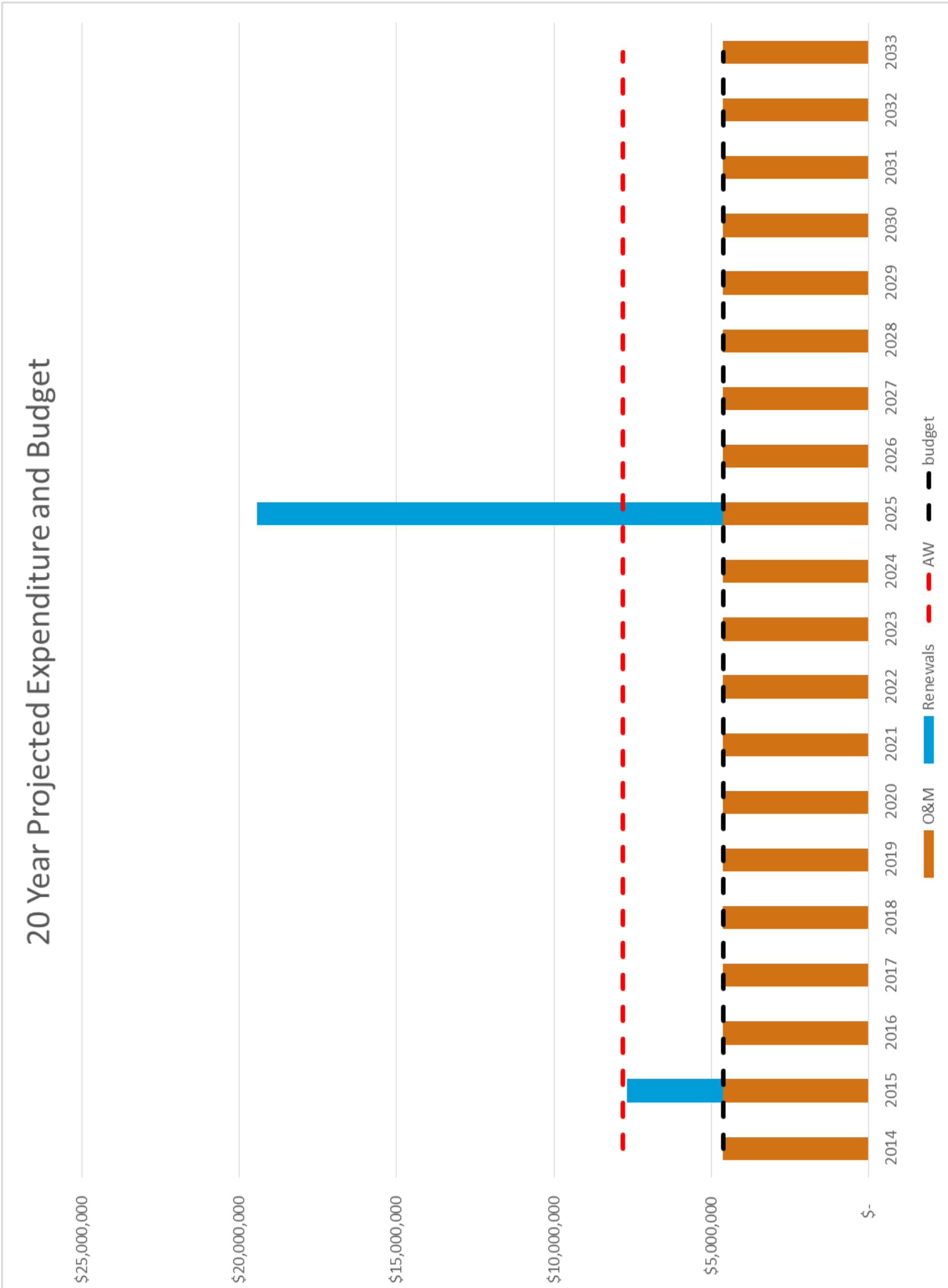


Figure D-4: RM of Wilton Existing Network Full Life Cycle Cost Profile – Including Uncertainty at Expected Values